

Removal of Fluoride from Drinking Water Supplies by Activated Alumina



SCIENCE

Design Manual
Removal of Fluoride from Drinking Water Supplies
by Activated Alumina

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DISCLAIMER

The information in this document has been funded by the United States Environmental Protection Agency (U.S. EPA) under Task Order (TO) No. 0012 of Contract No. EP-C-11-038 to Battelle. It has been subjected to the Agency's peer and administrative reviews and has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

ABSTRACT

This document is an updated version of the *Design Manual: Removal of Fluoride from Drinking Water Supplies by Activated Alumina* (Rubel, 1984). The manual is an in-depth presentation of the steps required to design and operate a fluoride removal plant using activated alumina (AA), which is a reliable and cost-effective process for treating excess fluoride from drinking water supplies.

For the design of an AA system, a list of critical items is provided as follows:

- Perform raw water analysis.
- Determine required/optimum system flowrate and utilization rate, maximum daily demands, as well as redundancy requirement, if any.
- Determine system configuration.
- Determine number of adsorption vessels and vessel dimensions (use an empty bed contact time [EBCT] of at least 5 min and a bed depth of 3 to 6 ft).
- Determine acid storage and feed subsystem requirements.
- Determine wastewater disposal needs.

For the startup and operation of an AA system, a list of critical items is provided as follows:

System Startup

- Half-fill adsorption vessels with water prior to placing underbed material and AA media.
- Thoroughly backwash vessels after leach lift of media loading.
- Measure free board in each vessel after placement of underbed material and media.
- Calibrate in-line pH meters.

System Operation – Treatment Mode

- Place one vessel in operation at a time.
- Adjust pH of influent water to pH 5.5 to 6.0.
- Raise pH of effluent water to no higher than 8.5.
- Extend a treatment run by blending.
- Take vessels offline for regeneration at a set breakthrough level; use staggered regeneration to minimize system downtime.

System Operation – Backwash Mode

- Drain bed for most effective backwash.
- Watch bed expansion and adjust backwash rate to avoid backwashing media out of vessels.
- Avoid excessive backwash.

System Operation – Regeneration Mode

- Use 1% NaOH at pH 13.0 for media regeneration.
- Adopt a one-step (upflow or downflow) or a two-step (upflow and then downflow) process for regeneration.
- Volume of caustic solution required per regeneration step is approximately 30 gal/ft³ of media.
- Regeneration flowrate is 2.5 to 3.0 gpm/ft² and regeneration time is 50 to 60 min per step.

System Operation – Neutralization mode

- Use sulfuric acid for media neutralization; pH of acidic water should be no lower than 2.5.
- Measure free board prior to replacing regenerated vessel into service; replenish media if needed.

A number of other treatment technologies are also available for removing fluoride from drinking water to levels below the maximum contaminant level (MCL) of 4 mg/L. These technologies are briefly reviewed in Section 2 of this design manual.

FOREWORD

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, EPA's research program is providing data and technical support for solving environmental problems today and building a science knowledge base necessary to manage our ecological resources wisely, understand how pollutants affect our health, and prevent or reduce environmental risks in the future.

The National Risk Management Research Laboratory (NRMRL) is the Agency's center for investigation of technological and management approaches for preventing and reducing risks from pollution that threaten human health and the environment. The focus of the Laboratory's research program is on methods and their cost-effectiveness for prevention and control of pollution to air, land, water, and subsurface resources; protection of water quality in public water systems; remediation of contaminated sites, sediments, and ground water; prevention and control of indoor air pollution; and restoration of ecosystems. NRMRL collaborates with both public and private sector partners to foster technologies that reduce the cost of compliance and to anticipate emerging problems. NRMRL's research provides solutions to environmental problems by: developing and promoting technologies that protect and improve the environment; advancing scientific and engineering information to support regulatory and policy decisions; and providing the technical support and information transfer to ensure implementation of environmental regulations and strategies at the national, state, and community levels.

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ACRONYMS AND ABBREVIATIONS

AA	activated alumina
ADA	Americans with Disabilities Act
AIX	anionic exchange
ASME	American Society of Mechanical Engineers
AWWA	American Water Work Association
BTGA	best technologies generally available
BV	bed volumes
CDC	Centers for Disease Control and Prevention
CO ₂	carbon dioxide
CPVC	chlorinated polyvinyl chloride
CWS	community water system
EBCT	empty bead contact time
ED	electrodialysis
EDR	electrodialysis reversal
EPA	United States Environmental Protection Agency
EPDM	ethylene propylene diene monomer
EPTDS	entry point to the distribution system
FRB	fiberglass and fiber re-enforced plastic
FRP	fiber-reinforced plastic
GAC	granular activated carbon
gpd	gallon per day
gpm	gallon per minute
HDPE	high density polyethylene
HHS	Health and Human Services
HVAC	heating, ventilating, and air conditioning
IC	ion chromatography
IX	ion exchange
MCL	maximum contaminant level
MCLG	maximum contaminant level goal
MGD	millions of gallons per day
NEC	National Electrical Code
NF	nanofiltration
NRC	National Research Council
O&M	operating and maintenance
OSHA	Occupational Safety and Health Administration
PAC	powder activated carbon
PHS	U.S. Public Health Service

PLC	programmable logic controller
POE	point-of-entry
POTW	publicly-owned treatment works
POU	point-of-use
PVC	polyvinyl chloride
RO	reverse osmosis
SDWA	Safe Drinking Water Act
SMCL	secondary MCL
SSCT	small system compliance technologies
TCLP	Toxicity Characteristic Leaching Procedure
TDS	total dissolved solids
TOC	total organic carbon
WET	Waste Extraction Test
ZPC	zero point of charge

1.0: INTRODUCTION

1.1 Purpose and Scope

The United States Environmental Protection Agency (EPA) published a fluoride design manual in 1984 to present the design, operation and cost information of central treatment plants for fluoride removal from water supplies using activated alumina (AA) (Rubel, 1984). While the manual continues to be a very useful document to small and large water systems containing high fluoride, improvements in the design and operation of the AA process have been made during the past 30 years. The capital and operating costs of AA systems have also changed significantly since then.

The information provided in the original and this revised design manual applies primarily to central treatment plants with capacities ranging from 30,000 to 1,000,000 gallon per day (gpd). However, the treatment information, for the most part, can be adapted to both larger and smaller systems. For very small systems with capacities of less than 30,000 gpd (~20 gal/min [gpm]), less expensive tanks such as fiber-reinforced plastic (FRP) canisters and valves likely would be used.

Several other treatment methods have also been used for removal of excess fluoride, but none with the cost-effectiveness and process efficiency of the AA method. AA and these alternative treatment methods and their limitations are reviewed in Section 2 of this revised design manual.

When excess fluoride is present in combination with quantities of other organic and/or inorganic contaminants, the AA process may not be the most effective method for fluoride removal. Those water supplies should be evaluated on a case-by-case basis for selection of the appropriate treatment method, or combination of methods for contaminant removal.

For the most part, this manual is prepared for engineering firms that design AA systems, but certainly can be used by others. For the very small systems, they would likely just ask for proposals from system suppliers without the use of an engineering design firm.

1.2 Fluoride Regulation

The Safe Drinking Water Act (SDWA) of 1974 mandated that EPA identify and regulate drinking water contaminants that may have an adverse human health effect and that are known or anticipated to occur in public water supply systems. In 1975, EPA proposed an interim primary drinking water regulation for fluoride of 1.4 to 2.4 milligrams per liter (mg/L) (temperature-dependent) to prevent the occurrence of objectionable enamel fluorosis, mottling of teeth that can be classified as mild, moderate, or severe. In 1986, EPA established a maximum contaminant level goal (MCLG) and a maximum contaminant level (MCL) for fluoride at a concentration of 4 mg/L (to protect against crippling skeletal fluorosis) and a non-enforceable secondary MCL (SMCL) of 2 mg/L (to protect against objectionable dental fluorosis). These guidelines are restrictions on the total amount of fluoride allowed in drinking water (and should not be confused as recommendations about adding fluoride to drinking water to protect the public from dental caries). In early 1990s at the request of EPA, the National Research Council (NRC) independently reviewed the health effects of ingested fluoride and the scientific basis for EPA's MCL and concluded in 1993 that the MCL was an appropriate interim standard but that further research was needed to fill data gaps on total exposure to fluoride and its toxicity (NRC, 1993).

Because new research data on fluoride became available since then, EPA, upon completion of its first six year review of the relevant drinking water standards in 2003, requested that NRC again review the adequacy of its MCLG and SMCL for fluoride. In response, NRC convened a committee and published a

report in 2006, in which it concluded unanimously that the present MCLG of 4 mg/L should be lowered to cope with the risk of developing enamel fluorosis, a condition associated with enamel loss and pitting for children (NRC, 2006). The majority of the committee also concluded that the MCLG is not likely to be protective against bone fractures.

Although no revision was established after the release of the 2006 NRC report and completion of its second six year review in 2010, EPA announced in a joint press release with the Health and Human Services (HHS) on January 7, 2011, steps to ensure protection of Americans, especially children, by the Fluoride Regulation, including plans to review the current 4.0 mg/L standard. Soon after, HHS proposed via *Federal Register* (2011) that the recommended optimal fluoridation level to prevent dental caries be set at 0.7 mg/L, the lowest end of the 0.7 to 1.2 mg/L range set previously by HHS.

1.3 Fluoride in Water Supplies

Fluoride occurs naturally in groundwater via weathering/leaching of rocks and soils containing fluoride-bearing minerals such as fluorspar (CaF_2), cryolite (Na_3AlF_6) and fluorapatite ($3\text{Ca}_3[\text{PO}_4]_2 \cdot \text{Ca}[\text{F},\text{Cl}]_2$) (Mackay and Mackay, 1989; Cotton and Wilkinson, 1988). Atmospheric deposition of fluoride-containing emissions from coal-fired power plants and other industrial sources also contributes to the presence of fluoride in surface water. Fluoride exists in water as fluoride ion (F^-). According to a survey performed by Centers for Disease Control and Prevention (CDC, 1993), over 170 water systems in the U.S. were supplied by water containing over 4 mg/L of fluoride. Based on sampling conducted in 16 states in 2002, EPA estimated that a total of 106 water systems had a system mean concentration exceeding the threshold of 4 mg/L and a total of 603 water systems exceed the threshold of 2 mg/L (EPA, 2003). The number of water utilities containing more than 2.0 mg/L of fluoride in the finished water was much higher at 1,200 as reported by the U.S. Public Health Service (PHS, 1969). Higher fluoride concentrations were usually found in western and southern states, such as Idaho (e.g., 15.9 mg/L), New Mexico (e.g., 13.0 mg/L), Oklahoma (e.g., 12.0 mg/L), Colorado (e.g., 11.2 mg/L), Texas (e.g., 8.8 mg/L), and Arizona (e.g., 7.4 mg/L).

1.4 Available Treatment Technologies

Activated alumina has been shown, in the field, to be effective in fluoride removal, especially by paying close attention to pH control during service cycles. Upon exhaustion, the spent media can be effectively regenerated by means of pH adjustment using caustic. Other adsorptive media have also been developed more recently but most, if not all, have been tested only in the laboratories with little or no full-scale application data. Membrane technologies, such as reverse osmosis (RO), nanofiltration (NF), and electrodialysis (ED), have also been utilized to separate and remove fluoride along with other contaminants such as total dissolved solids (TDS), arsenic and uranium. In general, these technologies are more complex to operate and more costly. Section 2 of this manual provides detailed reviews of available treatment technologies for fluoride removal.

2.0: TREATMENT METHODS FOR FLUORIDE REMOVAL

2.1 Introduction

According to the 1986 Fluoride Regulation, community water systems (CWSs) that use source waters containing excess fluoride must reduce its level to below the MCL at each entry point to the distribution system (EPTDS). CWSs in the U.S. are defined as systems with at least 15 service connections or that serve 25 or more persons year-round. EPA provides guidance on available treatment technologies, residuals produced by each technology, disposal options, and relevant regulations governing these options (EPA, 2003; 1986). For each EPTDS exceeding the MCL, a system must consider a mitigation strategy such as existing treatment optimization/modifications or new treatment installation if it cannot achieve compliance through a non-treatment option.

EPA recommends that a system first determine if its existing treatment technology is capable of removing fluoride even though it was not originally designed to do so. If non-treatment options or treatment modifications are ruled out, treatment may be accomplished either at the wellhead with a centralized treatment system, or at point-of-use (POU) or point-of-entry (POE) locations within a building or entering a building.

2.2 Non-Treatment Options

Non-treatment options do not produce residuals, usually are less expensive, and do not require any additional operator training. Typical non-treatment options include switching to a new or better source, blending, and interconnecting with and/or purchasing water from another water system (EPA, 2012).

Switching to another source may involve drilling a new well in an aquifer containing low fluoride levels, sealing off water producing zones containing high fluoride levels, or finding an uncontaminated surface water source. Before switching, attention must be given to water quality of the new source so that it does not interfere with the existing treatment process(es). Significant changes in water quality may require new treatment processes, impact the distribution system, and cause other compliance issues. Switching to another source also may be limited by the availability of new sources, existing water rights, and/or costs for transporting the new source water to the treatment plant.

Blending involves diluting fluoride concentrations of a contaminated source with another source containing low or no fluoride. To minimize piping required to carry the sources to a common mixing point, it would be ideal for the sources to be close to each other. Mixing usually occurs in a storage tank or a common header with resulting fluoride concentrations below the MCL or certain percentages (as safety factors) of the MCL set by authorized regulatory agencies. Similar to switching to another source, care should be taken to any changing water quality.

Characterization of water quality must be carried out to ensure that changes in water quality resulting from blending are assessed and that potential impacts to the existing treatment processes and distribution system are determined (EPA, 2012). Also any change in water quality should not cause other compliance issues. Blending may require specific regulatory approval.

Interconnecting with another water system must consider if there is a nearby CWS meeting the requirements of the Fluoride Regulation, if the system is willing to interconnect or consolidate, and if the system can handle increased demand from additional customers. Costs and the impact of interconnection on water quality and the distribution system also need to be considered in the decision-making process. In general, as the distance increases, the rise in elevation increases and the existence of physical barriers

occurs, the cost of installing a delivery system and delivering the water becomes increasingly unfavorable.

Use of bottled water is also an option. The reliability, cost and assurance that the consumers will use that source are some of the deterrents to be considered.

2.3 Centralized Treatment Options

Common centralized treatment options for fluoride removal include AA and RO, both of which are identified by EPA as the best technologies generally available (BTGAs) for fluoride removal based on technological efficiency and economic accessibility (EPA, 2003; 1986). Centralized AA and RO treatment and POU RO are also identified by EPA as small system compliance technologies (SSCTs) (EPA, 2003; 1986). For water systems requiring only fluoride removal, AA is the preferred treatment method. RO is the recommended process when, in addition to fluoride, TDS and other contaminants also need to be removed.

Removal of fluoride by AA relies on exchange of fluoride ions (and some anionic contaminant ions such as arsenic) for hydroxides on alumina surface, a process that is generally known as adsorption (although ligand exchange may be a more appropriate term for the process involved [Clifford, 1999; Stumm, 1992]). In addition to AA, other adsorbents such as bone, bone chars, and a variety of more recently developed materials also utilize adsorption/ligand exchange to achieve fluoride removal from water supplies.

RO utilizes a semi-permeable membrane and an applied pressure that overcomes the osmotic pressure to achieve fluoride removal. In addition to fluoride, many types of molecules and ions are also separated and removed. Several other membrane processes have also been used for fluoride removal. These include NF, ED, and electrodialysis reversal (EDR).

Conventional coagulation/filtration, lime softening, and somewhat modified methods, such as the Nalgonda technique, also have been suggested for fluoride removal. These processes rely on adsorption and co-precipitation of fluoride and other contaminants such as turbidity, color, and/or hardness during the formation of aluminum flocs or magnesium hydroxide.

Methods to remove fluoride from water supplies have been reviewed by many researchers and professional/government organizations both in the U.S. and abroad. Among the example articles and reports are American Water Work Association (AWWA) (2011, 2004), National Health and Medical Research Council (NHMRC, 2011), Health Canada (2010), Mohapatra et al. (2009), Shrivastava and Vani (2009), Cooperative Research Center (CRC, 2008), Onyango and Matsuda (2006), Fawell et al. (2006), Meenakshi and Maheshwari (2006), Pickard and Bari (2004), EPA (1998), and Sorg (1978).

2.3.1 Adsorption/Ligand Exchange Processes

2.3.1.1 Granular Activated Alumina. AA has been used since the 1940s as an effective adsorptive media for fluoride removal (Sorg, 1978; Maier, 1947, 1953). It is a mixture of amorphous and gamma aluminum oxide ($\gamma\text{-Al}_2\text{O}_3$) prepared by low-temperature (300 to 600°C) dehydration of $\text{Al}(\text{OH})_3$ precipitates. The material is highly porous and has a high average surface area per unit weight of 350 m^2/g of media. Adsorption occurs at both internal and external surfaces of AA.

The adsorptive capacity for fluoride by AA is pH-dependent, with fluoride best adsorbed below a pH of 8.2 – a typical zero point of charge (ZPC) – where alumina surface has a net positive charge. The maximum removal capacity generally is achieved at pH between 5.5 and 6.0 (Clifford, 1999; Schoeman

and Leach, 1987; Rubel and Williams, 1980; Choi and Chen, 1979; Rubel and Woosley, 1978), although other optimum pH values also have been reported (e.g., at 4.4 [Goswami and Purkait, 2012], 7.0 [Ghorai and Pant, 2004], and 5.0 to 8.0 [Choi and Chen, 1979]). Therefore, adjusting the pH of source water provides removal capacity advantages. As the pH values deviate upwardly from the 5.0 to 6.0 range, the adsorptive capacity for fluoride decreases at an increasing rate. Over-adjusting the pH to below 5.0, however, can result in gradual dissolution of the media (Hao and Huang, 1986).

A common AA mesh size is 28×48 (Tyler Equivalent). Larger mesh sizes can be used, but their capacities for fluoride are lower (Clifford, 1999). A larger mesh size such as 14×28 is also recommended by some media suppliers as a starting media size distribution, which is reduced with regeneration to effectively become an operating mesh size of 28×48 over time. The use of larger mesh sizes can extend the media life before losing the media as fines to the backwash cycles. Finer mesh materials have not been used for this application other than in laboratory bench-scale work (AWWA, 2011, 2004) because they cause pressure-drop and backwash problems.

A typical AA system consists of two or more packed-bed adsorbers configured in parallel or in series. In general, the in-series configuration yields the highest fluoride loading on the media and the lowest fluoride level in the treated water. The parallel configuration provides greater flexibility in treatment flowrate and system operations. Because it uses two large tanks to accommodate the design flowrate through each tank, an in-series system generally is more expensive. Downflow is a typical mode of system operation, although an upflow fluidized system may produce a greater fluoride removal capacity than does a downflow system (Bishop and Sansoucy, 1978). Media attrition in an upflow system can result in excessive media fines and cause premature media replacement especially under high loading rates. Most media and system suppliers recommend an empty bed contact time (EBCT) of 5 min (equivalent to 1 ft³ of media per 1.5 or 1.0 gpm of treated water flowrate) across each of two lead-lag beds. A more conservative EBCT of 7.5 min was referenced in the 1984 design manual when the beds are configured in parallel. For a given EBCT and a system design flowrate and a bed depth of 3 to 5 ft, a vessel diameter can be calculated.

Typically, a fluoride breakthrough curve from an AA bed is not as sharp as that from an ion exchange (IX) resin bed (Clifford, 1999), thereby making blending more difficult to implement. To maximize the media run length, one or more product water storage tanks can be utilized to equalize effluent fluoride concentrations and achieve a target effluent level through the service cycles.

The useful AA bed life is usually measured by the number of bed volumes (BV) of water treated before breakthrough of fluoride at a target level (e.g., 1.5 mg/L). Depending on the water quality and operating conditions, an AA bed can last from several hundred to a few thousand BV before media regeneration is required (AWWA, 2011; Schoeman et al., 2006; Schoeman, 2009; EPA, 1980). Table 2-1 presents a few run length test results reported in the literature. As expected, influent water pH significantly affects the system run length.

Spent AA can be regenerated using caustic soda. Fluoride along with other contaminants such as arsenic, selenium and organic molecules also adsorbed during the service cycle are removed during the process. A 1% NaOH solution is effective in removing fluoride, but not as effective in removing more highly charged contaminant ions, such as arsenic. If desired, higher strengths of caustic can also be used to regenerate AA, but will result in more media dissolution. Regeneration usually involves steps such as:

- Backwash to remove media fines and sediments and to fluff the media bed
- Drain the media vessel

- Apply caustic upflow through the vessel with a slow flowrate (some facilities use both upflow and downflow during this caustic wash step)
- Apply rinse water and then acidic water at pH 2.5 and then 4.0 (using sulfuric acid) downflow through the vessel

Table 2-1. AA System Run Length Results

Study Type	Influent Fluoride Level (mg/L)	Influent pH (After pH Adjustment) (S.U.)	Run Length (BV)/ Target Fluoride Breakthrough Level (mg/L)	Other Relevant Water Quality Parameters	Reference
Bench-Scale POU Devices	10.5	7.9–8.0	167/1.5	Alkalinity 325 mg/L ^(a) Hardness 360 mg/L ^(a) Sulfate 55 mg/L	Chauhan et al., 2007
Full Scale	5.3–10.8	6.6	566–780/ 1.9–2.1	Hardness 263 mg/L ^(a) Sulfate 139 mg/L	Schoeman et al., 2006; Schoeman, 2009
			728/1.5		
Pilot Scale	2.0	5.5–6.0	2,300/1.4	TDS 810 mg/L	AWWA, 1999
	3.0		1,200/1.4	TDS 1,350 mg/L	
	4.0		1,150/1.4	TDS 1,210 mg/L	
Pilot Scale	2.4–3.3	5.5–6.0	1,900 ^(b) /1.1 ^(c)	As 0.10 to 0.17 mg/L Hardness 105-108 mg/L ^(a) Sulfate 124-147 mg/L Silica 45 mg/L ^(e)	EPA, 1980
			3,800 ^(d) /1.1 ^(c)		

- (a) as CaCO₃.
- (b) Following lead column.
- (c) Average value.
- (d) Following lag column.
- (e) as SiO₂.

After media regeneration, the freeboard in the media vessel is often measured to determine if media replenishment is required before returning the vessel to the service cycle (an AA plant adds media prior to regeneration to take advantage of the backwash step during media regeneration). A marginal decrease in adsorptive capacity (e.g., 5% loss after five regeneration cycles [Ghorai and Pant, 2004]) can occur after each regeneration cycle. Much higher losses of adsorptive capacity (e.g., 30 to 40% [Fawell et al., 2006]; CRC, 2008) and media (e.g., 5 to 10% [Fawell et al., 2006; CRC, 2008]) have also been reported in the literature, and require replacement of spent media after only a few regeneration cycles. These unusually high losses are caused mainly by higher strengths (e.g., 4%) of caustic used.

Reduction in media capacity also may be caused by media fouling due to entrapped suspended solids, metal hydroxides, carbonates and adsorbed silica. The media capacity can be restored by using backwashing and air scouring with repeated rinsing and/or periodic acid treatment to remove silicate and hardness, as demonstrated by an investigation of the performance of two AA plants in South Africa (Schoeman and Leach, 1987).

Waste streams produced by media regeneration include spent caustic and alkaline rinse water. The most common disposal methods include direct discharge to a publicly-owned treatment works (POTW) via

sewer and to a lined evaporation pond (especially in arid areas). Some plants may opt to treat their regeneration waste streams to a clarifier where calcium chloride is added to form calcium fluoride precipitates, which are then processed through a filter press to form a sludge cake before final disposal.

Some small and very small systems may operate their AA plants without pH adjustment and media regeneration to avoid needs for strong acid/base storage and handling and waste stream disposal (EPA, 1998; Fox and Sorg, 1987).

Key advantages and disadvantages of using AA for fluoride removal include:

- AA is somewhat specific for fluoride; its capacity is not significantly affected by sulfate and chloride concentrations of the water. However, arsenic, selenium, and other inorganic ions (such as phosphate) and organic molecules (such dissolved organic matter) can compete with fluoride for available adsorption sites.
- Upon exhaustion, spent AA can be effectively regenerated using caustic followed by acid neutralization and a water rinse. The use of acid and caustic, often at the industrial strengths of 93% and 50%, respectively, is also the major disadvantage to the use of AA.
- AA is a relatively low cost media comparing to the costs of a synthetic anionic resin and bone char (Sorg, 1978).

Some of the earliest and longest-operating AA plants include:

- Bartlett, TX: The system was designed to remove 8 mg/L of fluoride initially. After a new well was developed with only 3 mg/L of fluoride, the system continued to operate with essentially the original media from 1952 through 1977 when the system was abandoned (Sorg, 1978; Maier, 1953). The raw water pH was adjusted to 7.0 during the entire operating period.
- Desert Center, CA: This 1968-built, 1,100-gpm manually-operated plant has two 14 ft × 16 ft cylindrical vessels configured in parallel. Due to corrosion, the two vessels had to be replaced with a carbon steel and a stainless steel vessel in 1995 and 2001, respectively. Currently, the gravity-flow system continues to operate with one tank at a time on a much reduced schedule (i.e., one day per week).
- Gila Bend, AZ: Built in 1978, this 900-gpm plant continued to operate through early 2000 before it was replaced by a three-train RO system for fluoride and arsenic removal.

The largest AA plant ever built in the U.S. is the Twentynine Palms Fluoride Removal Plant in California's Morongo Basin. Started in 2003, the 2,100-gpm (or 3 millions of gallons per day [MGD]) plant consists of three parallel treatment modules, each having two 11 ft × 12 ft vessels configured in series. The plant operates at an influent pH of 5.0 and an effluent pH of 8.0 after respective acid and caustic additions. The media beds are regenerated on a frequency of approximately one bed every three days at the current production rate of 1.25 MGD. The regeneration uses both upflow and downflow modes during the caustic wash step. Following the free-board measurement and media replenishment (media is currently added to the vessel prior to regeneration to utilize the backwash step during the regeneration process), the newly-regenerated vessel is switched to the lag position for continuing service. An average of 25% blending ratio is implemented to meet the statutory limit of 2.0 mg/L in California.

2.3.1.2 Bone, Bone Char, and Apatite-Based Materials. Bone was one of the first materials suggested for fluoride removal due to its known affinity for fluoride. Through ligand exchange (i.e., F⁻

for CO_3^-) on its main ingredient, carbonate apatite ($\text{Ca}_9[\text{PO}_4]_6\cdot\text{CaCO}_3$), a degreased, caustic-and-acid treated bone material was found effective in reducing fluoride concentrations from 3.5 to < 0.2 mg/L (Sorg, 1978). Because of its high cost, this material has not been widely used.

Another bone material, bone char, has been tested and used in several full-scale applications for fluoride removal. Originally developed for decoloring cane syrups in sugar manufacturing, bone char is ground animal bones charred to remove all organics and consists essentially tricalcium phosphate ($\text{Ca}_3[\text{PO}_4]_2$) and carbon. Similar to AA, bone char also removes competitive anions, such as arsenic, and can be regenerated with caustic upon exhaustion. Unlike AA, arsenic cannot be stripped off during normal caustic regeneration, thus rendering the material useless after a number of regeneration cycles (Sorg, 1978). The use of bone char can slough phosphate. Because it is more soluble in acidic water and more expensive than AA and because the treated water has a bad taste in some cases, bone char is not an economically viable option for fluoride removal.

Synthetic bone materials such as granular/powder tricalcium phosphate have been developed and used at a few full-scale plants in the 1940s. Due to less than satisfactory results (i.e., high attrition losses and diminishing capacities due to the presence of sulfate ions), these plants have been abandoned after several years of service (Sorg, 1978). More recently, there have been renewed interests in using synthetic bone materials, such as hydroxylapatite ($\text{Ca}_{10}[\text{PO}_4]_6(\text{OH})_2$), as low-cost adsorbents for fluoride removal in low-income countries (Sternitzke et al., 2012; Fan et al., 2003). Tests performed for these materials, however, have been limited mainly to material properties in the laboratories.

2.3.1.3 Ion Exchange Resins. IX is a common water treatment process that removes ionic contaminants via displacement of weaker binding, exchangeable ions on a resin. Removal of fluoride has been tested using strongly basic anionic exchange (AIX) resins containing quarternary ammonium functional groups, on which chloride ions are replaced by fluoride ions. Upon saturation, resins are regenerated with brine solutions to recharge the functional groups with chloride ions. Because of fluoride's low selectivity, the efficiency of the resins is significantly reduced in the presence of competing anions such as phosphate, arsenate, sulfate, carbonate, and alkalinity (Clifford, 1999). Due to this and other factors such as pretreatment requirements (to prevent resin fouling) and high costs, IX is not an economically viable treatment option for fluoride removal.

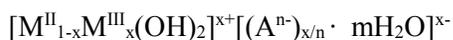
Special-purpose resins have been developed and tested recently in the laboratories for fluoride removal. The materials tested include La(III)-loaded polymethyl acrylate (PMA) resin, Zr(IV)-loaded Amberlite XAD-7 resin, La(III)-AFB resin, Pr(III)-AFB resin, Al(III)-AMPA resin, La(III)-impregnated silica gel, cross-linked pectic acid gel, phosphorylated cross-linked orange juice gel, and La(III)-loaded 200CT resin (Onyango and Matsuda, 2006). Except for the batch experiment results, not much is known about their long-term stability or large-scale operation. These materials are also expected to be expensive.

2.3.1.4 Other Adsorbents. In addition to AA and bone/apatite-based materials, a number of one-time use or regenerable novel adsorbents have been developed in recent years and are claimed, based mostly on laboratory test results, to be effective in reducing fluoride to below the relevant statutory limits. Behaving somewhat similarly to AA (e.g., being pH-dependent and affected by certain competing anions), many of these materials are found to possess greater adsorptive capacities, achieve more rapid uptake kinetics or be more economically affordable. Attempts were made to tabulate and compare test results of these materials against AA, but the tabulated entries are not necessarily comparable to one another due to significantly different test conditions used by various researchers. Further, by using mostly batch and some column experiments, most researchers reported only initial/influent and treated-water fluoride concentrations along with percent removal results (some also reported isotherm data). While being useful for demonstrating the materials' potential to become robust adsorbents, these data have rather limited values to reflect the materials' usefulness under the real world settings. As such, the

test results of these novel adsorbents are not discussed in this subsection. Those interested in any material are encouraged to read the specific articles as referenced below and Bhatnagar et al. (2011), which review the performance of over 100 novel adsorptive materials for fluoride removal under various conditions.

Examples of the newly developed novel adsorbents and existing low-cost materials tested include:

- Modified alumina such as manganese (di)oxide-coated AA (Teng et al., 2009; Tripathy and Raichur, 2008; Maliyekkal et al., 2006) and magnesia-amended AA (Maliyekkal et al., 2008)
- Nanomaterials such as nanomagnesia (Maliyekkal et al., 2010)
- Layered mixed metal oxides/hydroxides (or hydrotalcite-like compounds/anion clays), consisting of brucite-like hydroxide sheets with a general formula:



where M^{II} is a divalent cation like Mg^{2+} , Zn^{2+} , Cu^{2+} , etc., M^{III} is a trivalent cation like Al^{3+} , Cr^{3+} , Fe^{3+} , etc., and A^{n-} is an anion (Sujana and Anand, 2010; Onyango and Matsuda, 2006)

- Geo-materials such as bauxite (Das et al., 2005); limestone/calcite (Turner et al., 2005; Fan et al., 2003); fluorspar, quartz, and iron activated quartz (Fan et al., 2007); lanthanum, magnesium and manganese-impregnated bentonite clay (Kamble et al., 2009); and other low-cost clays and soils (Mohapatra et al., 2009; Onyango and Matsuda, 2006)
- Zeolites and surface-tailored zeolites (Onyango and Matsuda, 2006)
- Biopolymers such as chitin, chitosan, and Al or La-modified chitosan (Jagtap et al., 2011; Miretzky and Cirelli, 2011; Swain et al., 2009; Kamble et al., 2007) and Zr-impregnated collagen fiber (Liao and Shi, 2005)
- Carbonaceous materials such as Al-, Ti- and La-impregnated granular activated carbon (GAC; Jing et al., 2012; Onyango and Matsuda, 2006); calcium compounds-containing charcoals (Tchomgui-Kamga et al., 2010); biochar (Mohan et al., 2012) and other coal-based sorbents (Sivasamy et al., 2001)
- Waste-derived adsorbents such as alum sludge (Sujana et al., 1998); red mud (Mohan and Pittman, 2007); and waste residue from alum manufacturing process (Nigussie et al., 2007)
- Other low cost materials, such as ragi seed powder, horse gram seed powder, orange peel powder, chalk powder, pineapple peel powder, and multhani matti (Gandhi et al., 2012).

2.3.2 Membrane Processes

2.3.2.1 Reverse Osmosis and Nanofiltration. RO, a process that moves clean water (or permeate) across a membrane against the concentration gradient as a pressure that is higher than the osmotic pressure, is exerted on the side with the concentrated solution. The remainder of the feedwater along with rejected contaminants (or reject) is discharged as a concentrated waste stream. The effectiveness of the process and the amount of permeate produced (referred to as recovery rate) are heavily dependent on water quality, size and charge of contaminant ions, membrane properties, as well as system operating pressure, temperature and flowrate.

In general, larger and charged species are retained more easily by the membrane than smaller and uncharged species. “Tighter” membranes allow less solute passage than “looser” membranes. Increasing the operating pressure will force more water through the membrane, thus increasing the solute rejection rate. However, increasing the feed flowrate under a constant pressure, will reduce the system recovery and solute rejection rates. A higher feedwater temperature will increase the permeability of the membrane, thus lowering the operating pressure and solute rejection rate.

During the past decade, membrane manufacturers have developed RO membranes with pore sizes and operating pressures that lie between those of traditional RO and NF membranes. As such, RO and NF are on a continuum of membrane characteristics, rather than two distinct technologies. Due to larger pores, NF membranes offer less resistance to passage of both solvent (like water) and solutes, thus requiring less pressure to operate the systems. The low-pressure RO membranes are those with operating pressures that are close to those of traditional NF membranes.

When contaminants other than fluoride also need to be removed from source water, RO can be a good option for fluoride removal. The removal efficiency (or rejection rate) is high, ranging from 83 to 98% based on results of a pilot study that evaluated five commercially available RO membrane elements (EPA, 1988). A more recent study carried out in India also achieved a 95% fluoride rejection rate (Arora et al., 2004). Operating at an 80% recovery rate, a 1.6 MGD, extra low energy RO plant in Finland achieved a permeate fluoride concentration of <0.03 mg/L prior to 70% blending (Sehn, 2008). After more than three years of system operation, the plant maintained a salt and fluoride rejection rate as high as what was obtained during the initial system startup. Table 2-2 summarizes some reported fluoride removal results by either RO or NF.

Table 2-2. Fluoride Removal Efficiencies (Rejection Rates) by RO

Study Type	Influent Fluoride Level (mg/L)	Treated Water Fluoride Level (mg/L)	Removal Efficiency (or Rejection Rate) (%)	Reference
RO-LS	1.4–6.6	0.17–0.78	88–89	Arora et al., 2004
RO-LS	4.2–9.3	0.32–0.88	91–92	Meenakshi and Maheshwari, 2006
NF-BS	4.0–6.8	<0.19–1.67	62–97	Cohen and Conrad, 1998
NF-PS	1.8–20.0	0.07–2.79	50–99.5	Tahaikt et al., 2007
NF-PS	2.3–22.3	0.05–4.0	74–99	Tahaikt et al., 2008
NF-PS	13.5	0.7	94	Lhassani et al., 2001
NF-PS	5.0	NR	78–95	Diawara et al., 2005
NF-PS	2.8	0.6	79	Health Canada, 2010
RO-PS	5.3–14.5	NR	83–98	Huxstep and Sorg, 1988
NF-PS	4.7	0.03–0.06	98–99	Cohen and Conrad, 1998
RO-FS	1.3–1.8	<0.03	>97–>98	Sehn, 2008
RO-FS	3.3–5.6	0.33–0.56	90	Cohen and Conrad, 1998

BS = bench scale; FS = full scale; LS = laboratory scale; NF = nanofiltration; PS = pilot scale; RO = reverse osmosis

Limitations of the RO process include possible membrane scaling, fouling, and failure as well as higher energy and capital costs. Calcium, magnesium, and silica can cause scaling and decrease membrane efficiency. Colloids and bacteria can also cause fouling. Both fouling and scaling will increase pressure drop, thus decreasing membrane life and increasing energy costs. Pre-treatments such as softening and cartridge filtration and/or membrane cleaning can help obtain acceptable membrane run times.

Membrane failure can allow contaminants to pass through to the finished water. Membrane integrity testing through either pressure drop or markers or measuring parameters in the effluent such as TDS, turbidity, or particle counts can help alleviate the concern. Chlorine can damage RO membranes and should be quenched using de-chlorination chemicals or GAC.

Due to high pressure, full-scale RO is a more expensive treatment option for removing fluoride. Also, a RO unit can produce a large amount of reject water, e.g., from 10 and 70% depending on pressure drop and pore size. Increasing the number of membrane stages can increase the percent recovery and decrease the waste production.

Because RO removes alkalinity in water, it will lower product water pH and increase its corrosivity. Therefore, the product water pH must be adjusted to avoid simultaneous compliance issues in the distribution system such as elevated lead and copper.

During the past decade, a number of large, full-scale RO systems have been installed for the removal of fluoride and other contaminants. Among the example plants are Gila Bend, AZ (to replace an AA plant installed in late 1970s); Andrews, TX (to remove fluoride and arsenic); Wolfforth, TX (to remove fluoride and arsenic); Blythe, CA (this, as the main plant, and an AA plant supply water to a large state correction facility); and Maude, OK.

2.3.2.2 *Electrodialysis and Electrodialysis Reversal.* Originally developed for demineralizing water from brackish water sources, ED and EDR use an electrical current to separate ionic contaminants from the feedwater through semi-permeable membranes. In EDR, the polarity of electrodes is reversed periodically on a preset time cycle, thus causing a reversal in ion movement. The change in the direction of ion movement helps reduce scaling and eliminate the need for chemical conditioning. Because water does not physically pass through the membrane, particulate matter is not removed.

A basic EDR unit, commonly referred to as a membrane stack, consists of several hundred cell pairs bound together with electrodes on the outside. Feedwater passes simultaneously through the cells to provide a continuous, parallel flow of desalted product water and brine that emerge from the stack. A single pass EDR unit has 20 to 30% water loss; a sequential EDR unit can reduce water loss to 5 to 10%.

Results of a laboratory study showed that fluoride concentrations could be reduced to 0.67 mg/L when applying a 10 V current to a brackish water containing 3 mg/L of fluoride and 3,000 mg/L of TDS (Amor et al., 1998). Increasing the voltage to 15 V further reduced the concentration to 0.21 mg/L. A pilot study on a brackish water reported a reduction in fluoride concentration from 1.8 to 0.5 mg/L (Tahaikt et al., 2006).

Because of system complexity and costs, only a few full-scale ED/EDR systems are installed to date. A 3.8-MGD EDR system installed in Virginia reduced fluoride concentration from 4.8 to 1.2 mg/L (Thompson and Robinson, 1991). Another EDR system was installed in Thunderbird Farms Domestic Water Improvement District in Arizona (De Haan, 2011), but the relevant system performance data were not available at the time of this manual revision.

2.3.3 Other Centralized Treatment Methods

2.3.3.1 *Conventional Coagulation/Filtration.* Conventional coagulation/filtration is one of the most common water treatment processes for turbidity and color removal from water supplies. With the addition of an aluminum salt (i.e., alum), the process can remove fluoride (e.g., reduced from 3.6 to 1.0 mg/L), but the removal requires large doses (e.g., 350 mg/L), as demonstrated by early laboratory studies performed in the 1940s (Sorg, 1978). A more recent study used an alum and powder activated

carbon (PAC) slurry to reduce fluoride concentrations from 15 to 1.5 mg/L. High alum doses (i.e., up to 850 mg/L as $\text{Al}_2(\text{SO}_4)_3 \cdot 16\text{H}_2\text{O}$), again, were required to achieve the intended result (Mekonen et al., 2001). Similarly large doses (i.e., 80 mg of $\text{Al}_2(\text{SO}_4)_3$ per 1 mg of F^-) were used to remove fluoride from an Estonia water. Because these doses are much greater than those commonly used for turbidity and color removal, alum coagulation has not been considered a practical solution for fluoride removal.

2.3.3.2 Lime Softening. Lime softening is a precipitative process that removes calcium and magnesium ions from hard water. Lime and, perhaps, soda ash and/or magnesium carbonate are added to raise pH to up to 9.5 and greater than 10.6, respectively, resulting in calcium carbonate and magnesium hydroxide precipitates. Lime softening can remove fluoride from water, and the removal is a function of the amount of magnesium removed, according to some early laboratory studies performed in 1930s (Sorg, 1978). The mechanism involved is believed to be coprecipitation with magnesium hydroxide. Similar to alum coagulation, large quantities of chemical(s) are required for fluoride removal. Therefore, this method is adaptable to only low-fluoride-high-magnesium water requiring softening.

2.3.3.3 Nalgonda Technique. Considered a simple and economical method, the Nalgonda technique utilizes alum and lime followed by rapid mixing, flocculation, sedimentation and filtration to remove fluoride. The process involves dissolution of alum and development of aluminum hydroxide micro-particles to remove fluoride via electrostatic attachment during flocculation. Because the alum solution is acidic, simultaneous addition of lime is required to ensure a neutral pH and complete precipitation of aluminum. Compared with the conventional coagulation process, the Nalgonda technique requires a much larger dosage of alum and the fluoride captured in the aluminum hydroxide flocs can be released slowly back to water (Shrivastava and Vani, 2009). The process has been used for fluoride removal from water supplies in some parts of India (Nawlakhe and Rao, 1990; Bulusu et al., 1983; 1979).

2.4 Point of Use/Decentralized Treatment Technology

The POU technology uses devices that sit on a counter, attach to a faucet, or are installed under a sink to treat small amounts of drinking water at homes or other locations such as schools. They differ from POE devices, which are installed on the water line as it enters the home or a building and treat all the water in the building. POU RO is identified by EPA as an SSCT (EPA, 2003; 1986). A typical POU RO unit is composed of a prefilter (to remove suspended solids), a GAC prefilter (to remove chlorine), a RO membrane module, and, perhaps, a GAC postfilter before the outlet faucet.

Fox and Sorg (1987) investigated a commercial POU RO system in an EPA laboratory using Cincinnati tap water spiked with 5.95 mg/L of fluoride. Over 98% removal was observed during a four-day intermittent system operation.

In a guidance document published by EPA (2006) for small drinking water systems, four POU RO case studies, including one for a school and three for homes, were discussed for fluoride removal. All four units treated fluoride from mean influent levels of up to 6.1 mg/L to levels below the MCL. In the three household units, there were signs of bacterial growth in GAC postfilters. The issue in two of the studies was addressed by flushing the units, consumer education for more frequent use of the units, or flushing the distribution system to ensure a chlorine residual of at least 1.5 mg/L (as Cl_2) in the feed water.

Numerous POU RO devices are commercially available, for which NSF International has listed, as of June 2013, 30 different manufacturers as certified providers for fluoride removal under NSF/ANSI standard 058 (NSF International, 2013a). The standard requires certified devices to reduce fluoride from an average influent level of 8.0 mg/L to an effluent level of less than 1.5 mg/L (NSF International, 2013b). In general, these devices operate at rather low recoveries (e.g., 40%).

Although not as popular as POU RO devices, some POU units using AA or other adsorbents also are commercially available for fluoride removal (Natural Health Enterprises, 2013; National Fluoridation Information Service, 2012). These products, however, are not NSF International-certified.

Depending on the technology used, POU units can be more cost effective for very small communities that do not have the resources required to build a centralized treatment facility. Some states do not allow POU units for MCL compliance, primarily due to the challenge to develop an acceptable monitoring program for homeowners and systems that install POU units.

3.0: DESIGN OF CENTRALIZED ACTIVATED ALUMINA PLANT

When designing a centralized fluoride removal plant, a design engineer typically divides the project into three phases:

- (1) General Plan – The general plan encompasses the conceptual design with basic design information and is often required for regulatory agency review.
- (2) Preliminary Design Plan – The preliminary design plan typically includes the completion of 30% of system design drawings, which are used to establish a cost estimate and select potential major equipment suppliers.
- (3) Final Design Plan – The final design plan is the completion of the contract documents, which are used to bid and construct the treatment plant, subject to regulatory agency review and approval.

3.1 General Plan

3.1.1 General Considerations. The general plan is prepared to provide background information on the project and outline specific issues that must be addressed to treat the source water. The plan summarizes the basis of design for all elements of the project and evaluates those against any regulatory standards to make sure that regulatory compliance will be met. Key elements of the plan include an analysis of the source water, reliability of supply, evaluation of the appropriate treatment process, establishment of design data in accordance with regulatory requirements, and conceptual layout. Budget cost estimates are derived using general guidelines with conservative contingencies provided for unknown items, which may be determined during the preliminary and final design.

An analysis of the raw or source water is perhaps the most critical consideration during this phase of system design. Comprehensive raw water analyses of all inorganic, organic, radionuclide, and bacteriological contaminants can help verify that the AA process is applicable for fluoride removal. The data from the source water analysis will impact all aspects of system design, from selection of a treatment system to materials costs and labor. An example of the different types of information required for a raw water analysis is provided in Table 3-1.

Another major consideration at this phase is siting of the treatment plant. The most practical approach is to install the plant in such a location that expensive improvements do not need to be made in order to convey finished water to the customers of the plant. In some cases, existing well pumps can provide adequate flow and pressure through the plant. If the existing well pump is oversized (i.e., at a much higher flowrate than the peak requirement), it should be resized to deliver only slightly more (e.g., 125%) than the peak flowrate. Because the flowrate dictates the treatment equipment size and capital cost, the design flowrate should be minimized to the extent possible to ensure that the capital cost of the treatment system is minimized. The AA volume is a function of flowrate and EBCT. The treatment vessels, pipe sizes, and chemical feedrates all increase as the flowrate increases. A well-matched pump should be able to handle additional head loss associated with the treatment system without a significant drop in pump efficiency. If the additional head loss cannot be met with the existing pump, several options exist: increasing the size of the motor, increasing the size of the impeller, or replacing the pump. Reducing flowrate for an oversized pump can result in excessive equipment wear and energy cost.

Other items that need to be determined in the general plan may include the following:

- Present water consumption and the projected average and maximum daily demands.
- Fire flows that meet the recommendations of the insurance service office or other similar agencies for the service area involved
- Hours of operation, that is related to the system utilization rate.
- Redundancy requirements per relevant state regulations.
- Automatic or manual system operations. With manual operation, personnel must be available or on site during operation of the plant. Automatic operation can save labor costs if designed properly.
- Water storage facilities, which must be evaluated to balance the hours of operation against the sizing of the plant. In general, storage should be provided to contain a minimum of one half the maximum daily consumption requirement. This is based on the premise that maximum consumption takes place during 12 hr of the day. Then, if the system operates during the entire 24 hr, storage drawdown occurs during 12 hr and recovers during the remaining 12 hr.
- Construction materials that comply with Occupational Safety and Health Administration (OSHA) standards, local building codes, and health department requirements. Materials also must be suitable for the pH range of the water and be compatible with the use of pH adjustment and regeneration chemicals. Consideration for oxidants being used will determine the types of materials and ventilation system used in the treatment facilities. All chemicals used must be properly stored and all chemical storage facilities must meet all safety and containment requirements. Both drinking water chemicals and system components should comply with NSF/ANSI Standards 60 and 61, respectively.
- Protection of treatment system equipment from ambient weather. It is recommended that the system be housed within a treatment building, although housing is not mandatory in some locations.
- Options of wastewater disposal. This should be carefully evaluated in the design of any centralized water treatment plant. Wastewater resulting from backwash and regeneration of spent AA media must be disposed of in a manner permitted by state and/or local regulatory agencies. Separate local and state regulatory reviews may be required for wastewater disposal. Quantifying the backwash and regeneration waste and determining the disposal requirements also should be outlined.

A general plan report containing all of this information as well as a preliminary project estimate and schematic drawings should be submitted for review and approval by the appropriate authorities. This document can be used to establish funding requirements for the project. A determination of what funding is available should be made before the project is authorized for preliminary and final design. If the preliminary estimate of project costs exceeds the available funds, adjustments should be made to increase the funding or reduce the scope of the project. Figure 3-1 illustrates the steps of the project development process from project authorization through final design.

This design manual is applicable when fluoride removal is the only treatment required. Removal of other contaminants such as iron/ manganese, suspended solids, hardness, organics, and radionuclides also may be required. In those cases, alternative treatment processes and/or additional treatment processes must be evaluated.

The sequence of other treatment steps should be compatible with fluoride removal using AA. Removal of iron/manganese, suspended solids, hardness, and organics should take place upstream of the fluoride removal process. Disinfection with chlorine should take place after fluoride removal because it has been noted that chlorine can degrade the performance of activated alumina (Rubel, 1984). Although no known investigation has determined the amount of chlorine that can be tolerated by AA, process degradation has been eliminated on projects where prechlorination was terminated (Rubel, 1984). Other treatment processes may be required upstream of the fluoride removal process, but that decision will be made on a case-by-case basis.

Table 3-1. Example of Fluoride Removal Plant Water Analysis Report

Name and Address: _____ Source of Water: _____
 Container: _____
 Sampling Date: _____
 Sampled by: _____

Analysis No.	#1	#2	#3	
Sodium (mg/L)				
Calcium (mg/L)				
Magnesium (mg/L)				
Total Iron (mg/L)				
Soluble Iron (mg/L)				
Total Manganese (mg/L)				
Soluble Manganese (mg/L)				
Aluminum (mg/L)				
Chloride (mg/L)				
Fluoride (mg/L)				
Nitrate (mg/L as N)				
Nitrite (mg/L as N)				
Ammonia (mg/L as N)				
Sulfate (mg/L)				
Silica (mg/L) (mg/L as SiO ₂)				
Arsenic (µg/L)				
Phosphate (mg/L as P)				
Total Alkalinity (as CaCO ₃)				
Total Hardness (as CaCO ₃)				
Total Dissolved Solids (mg/L)				
Total Organic Carbon (mg/L as C)				
Turbidity (NTU)				
Color (Units)				
pH				
Temperature (°F)				
Specific Conductance (micro-mhos)				

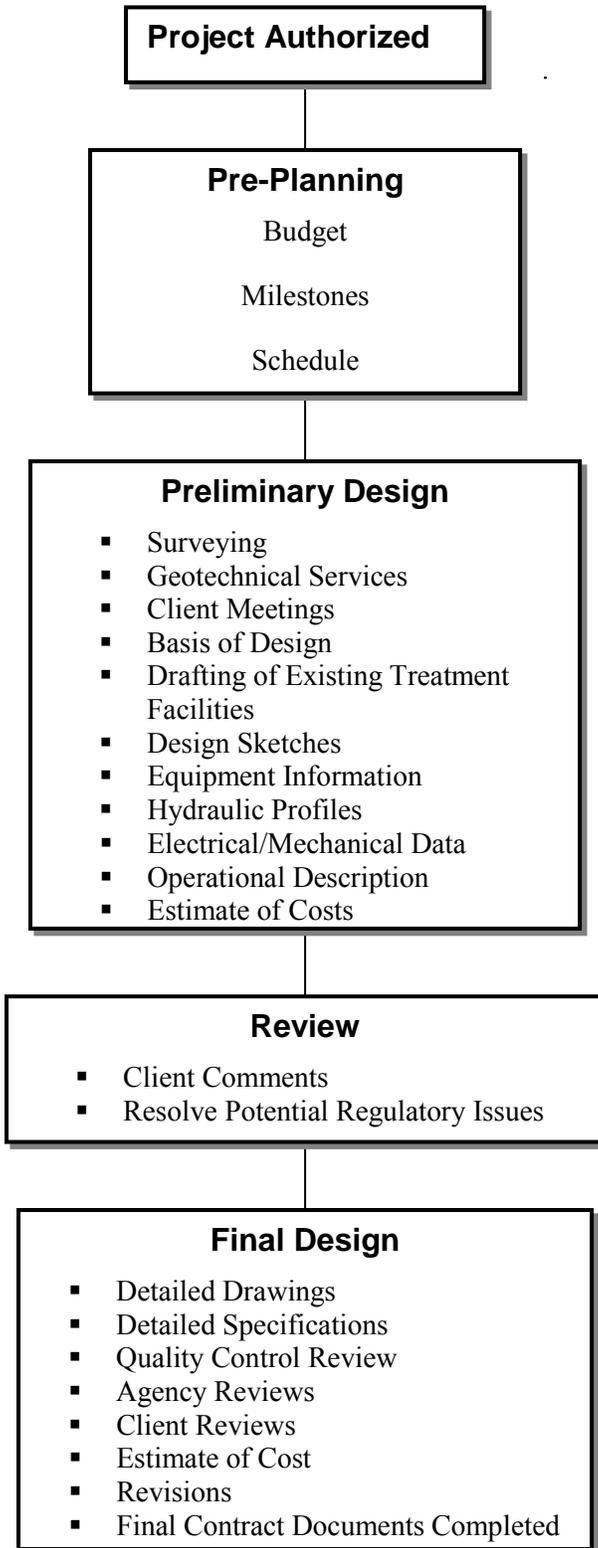


Figure 3-1. Project Development Process

3.1.2 Conceptual Design. Several conceptual design issues are to be considered in the general plan. These design considerations provide a conceptual delineation of the process, but do not provide specific details in equipment size, arrangement or material selection. There are four basic options from which a conceptual design can be selected. While every combination of the operation can perform the process but, under a select set of conditions, a certain combination may be preferred. The options are as follows:

- (1) Gravity or pressure flow
- (2) Single or multiple AA vessel(s)
- (3) Up- or downflow direction
- (4) Series or parallel vessel arrangement.

The most cost-effective AA configuration is a downflow multiple-bed pressure system arranged in parallel. However, some large plant operators and media suppliers prefer the use of multiple lead-lag trains. The lead-lag configuration yields the highest fluoride loading on AA and the lowest treated water fluoride concentrations, but requires more capital investment. The single treatment unit configuration is less efficient unless there is an exceptionally large treated water storage capacity. In that case, the economy of treated water blending can take place in storage. Because of the space and capital requirements, this is not an economic option.

A gravity flow system does not provide the economics of a pressure system; the treatment flowrate is lower; re-pumping of treated water is always required, and capital costs are higher. Because free carbon dioxide (CO₂) is released to the atmosphere in a gravity system utilizing pH adjustment, it is easier to control pH in a pressure system. Downflow treatment has consistently yielded higher fluoride removal efficiency than upflow. Because downflow utilizes a packed bed, the flow distribution is superior. If upflow beds are restrained from expanding, they would in effect also be packed. However, they would forfeit the necessary capability to backwash. Once the bed configuration is defined, a basic schematic flow diagram is prepared (see Figure 3-2). This diagram presents all of the subsystems required for pH adjustment and media regeneration. A summary of subsystem components is presented in Appendix A.

For systems in which the raw water fluoride concentration is slightly above the fluoride MCL, bypassing and blending a fraction of raw water with AA-treated water should be evaluated. This option saves treatment chemicals, extends treatment media cycle life, and reduces operating costs. If bypassing and blending is found to be feasible, the treatment system can be sized to treat less than 100% of the total flow. Plants with less budget constraints can still size their systems to 100% of the total flow to allow for blending volume adjustments.

Treatment of regeneration wastewater can be handled by several different processes, and therefore, is beyond the scope of this design manual. For the purpose of this manual, a lined evaporation pond is used for disposal of regeneration wastewater, but is applicable in arid climates where evaporation rates are high and land required for the basins is available at low costs. In regions where evaporation rates are low, backwash and regeneration wastewater can be neutralized and contained in a surge tank from which slow discharge to a sewer system is permissible. This latter disposal method can only be used when local regulatory agency approval is provided.

Prior to proceeding with the preliminary design, financial feasibility should be determined. Funding limits for the project should be defined. A determination that funding is available to proceed with the project should be made; this requires a preliminary rough project estimate with an accuracy of $\pm 30\%$. If the preliminary rough estimate exceeds the available funds, adjustments should be made to increase funding or reduce the project scope.

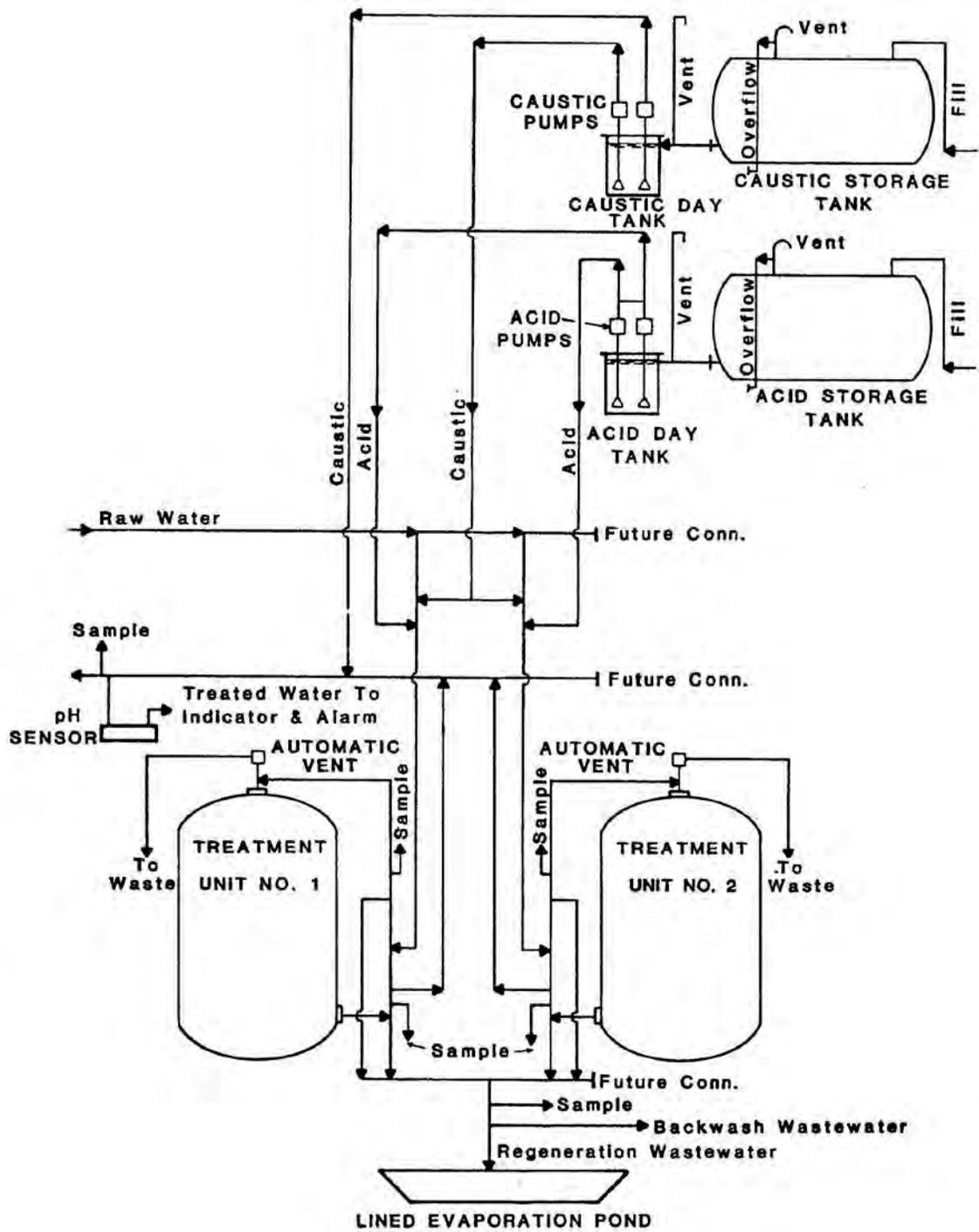


Figure 3-2. An Example Parallel Flow Diagram

3.2 Preliminary Design

After completion and approval of the conceptual design by the client, the regulatory agency(s), and any other affected party, preliminary design can begin.

3.2.1 Basis of Design. The basis of design is a document, outline, or strategic plan that is developed early in a water treatment system project to record and summarize decisions that have a major and extensive impact on project design and implementation. The basis of design also helps minimize late changes, additions, or modifications to the project, as well as the high expenses commonly associated with late changes. The development of the basis of design should not be performed solely by the project manager; the owner of the water treatment system must have opportunity to review and comment on the content of each design element. The following subsections discuss elements that should be addressed in a basis of design.

3.2.1.1 General

- (1) State the purpose of the project (i.e., what problem is the project designed to correct?).
- (2) Identify areas of new or unique design and provide criteria.
- (3) Identify areas where evaluation of alternatives must first be completed before initiating final design. Identify alternatives to be evaluated.
- (4) Identify critical structures, processes, or complex areas that require early engineering and design effort to avoid later delays.
- (5) State major constraints such as maximum construction cost, and court-imposed or client-imposed deadlines.
- (6) Note availability of prior drawings and dates when previous on-site project work was done.
- (7) Note major potential trip-up items (i.e., power availability, flood plain location, historic register, property or easement availability, financing, etc.).
- (8) Identify provisions to be made for future construction and expansion, beyond present scope, for sizing of or location of structures or equipment.
- (9) Note who has jurisdiction for permit approvals (i.e., plumbing, electrical, building, elevator, elevated tank, groundwater protection, EPA, etc.).
- (10) Identify unusual situations that will affect design (i.e., rock, unstable soil, high groundwater, corrosion).
- (11) List specific points where client has expressly requested to be advised of design decisions, or where client will require involvement of staff in decision-making.
- (12) Identify hazards or hazardous areas (i.e., asbestos, windowless building story, confined space, fire, National Electrical Code (NEC) explosion areas, corrosion, fumes, dust, odor). For asbestos, determine responsibility for discovery, arrange testing, and determine level of abatement required.
- (13) Identify large or complex structures that will require special building code compliance review prior to initiating final design.

3.2.1.2 *Project Scope*

- (1) Provide a schematic process flow diagram (i.e., show such items as water or wastewater flow, chemical feed, site sanitary sewer, and drain piping).
- (2) Provide a list of building, structures, and equipment.
- (3) Based on client's input, identify major equipment or brands of equipment to be used or not used.
- (4) Prepare tentative list of plan sheets.

3.2.1.3 *Process Design Data Summary*

- (1) List design data summary. Note average, maximum, and peak hydraulic flowrate capacities. Define concentrations to be removed or treated.
- (2) Identify "design parameters" and "units furnished" for each unit process or major equipment item.

3.2.1.4 *Site*

- (1) Provide a simple site plan with locations of existing and new structures, including sanitary and storm-water pumping stations as applicable.
- (2) Note any special consideration related to design (i.e., location in flood plain, dike construction, location to adjacent residential areas or parks, requirements for site clearing, major underground facilities that will affect location of new improvements).
- (3) Summarize concept for removing stormwater from site.
- (4) Identify any site constraints (i.e., required area set aside for future expansion, other client land uses).
- (5) Identify structures to be demolished.
- (6) Determine general fencing requirements and whether motorized gates are desired.
- (7) Identify extent of landscaping if desired by client.
- (8) Identify 100-year flood plain elevation if applicable.

3.2.1.5 *Layout of Structure*

- (1) Identify approximate structure size and preliminary location of rooms and/or major equipment on a floor plan.
- (2) Determine building(s) use group, fire resistance ratings, ceilings, stairwells, height and area restrictions, special fire and life safety requirements, and means of egress strategy to at least the level that they will affect preliminary building layouts and costs. Address requirements of the Americans with Disabilities Act (ADA).
- (3) Coordinate location and layout of chlorine, acid and base rooms.
- (4) Identify particular client preferences early for architectural details.
- (5) Determine architectural style and requirements, with consideration to insulation requirements:

- (a) Wall construction (i.e., brick and block, concrete block, glazed structural block, sound block, metal siding, pre-engineered, aggregate panels).
 - (b) Roof construction (i.e., pre-cast concrete, poured-in-place concrete, steel deck and bar joists, wood trusses). Consider type of structure and its interior use (i.e., wet areas, chemical feed area, etc.).
 - (c) Roofing materials (i.e., single-ply ballasted or adhered membrane, built up, shingles, metal).
 - (d) Windows (i.e., natural light, ventilation, aesthetics). Match or replace existing windows: material (i.e., aluminum, steel, wood, vinyl) and/or finish (i.e., anodized, painted, primed).
 - (e) Doors. Match or replace existing doors: material (i.e., hollow metal, aluminum, FRP, stainless steel, wood, acoustical).
 - (f) Overhead and/or roll-up doors. Identify electric operator versus manual lift doors.
- (6) Provide room finish schedules based on client input. Items to include are listed as follows:
- (a) Interior wall construction (non-load bearing); material (i.e., concrete block, glazed block, steel or wood stud walls); finishes (i.e., unfinished, painted, gypsum board, wallpaper, paneling, chair railing, molding at ceiling and floor).
 - (b) Flooring. Unfinished or sealed concrete, seamless floor covering, vinyl, carpeting, tile (i.e., thin-set or thick-set), terrazzo, applied composite material with urethane overcoats, embedded steel mats where heavy steel wheel loads are anticipated (i.e., dumpster containers).
 - (c) Ceilings. Material and finishes.
- (7) Identify stair type (i.e., concrete pan, metal, cast in place).
- (8) Identify method of removing rainwater from roofs of each building and point of discharge (i.e., roof drains, gutters and downspouts, roof scuppers discharging to ground, or storm sewers).
- (9) Identify locations of rest rooms (for both genders) in building.
- (10) Identify locations of drinking fountains and coolers.
- (11) Identify areas where service sinks or portable sampler wash down basins will be provided.
- (12) Specify grating material (i.e., aluminum, steel, FRP such as in certain chemical feed and fill areas).
- (13) Determine extent of laboratory improvements.
- (14) Identify any existing structures to be re-roofed or repainted.
- (15) Write preliminary outline of requirements for OSHA (i.e., signing, color coding, fire extinguishers) and ADA.

3.2.1.6 Structural

- (1) Identify local code requirements for seismic design, frost depths, wind loads, and snow loadings.
- (2) Identify design of live load requirements for stairway, office, and corridor floors. Also floor loadings for operating and storage areas.
- (3) Identify design for water, earth, and live load requirements for foundation walls.

- (4) Identify likely areas where peripheral drains and hydrostatic pressure relief valves will be necessary to prevent flotation and reduce exterior pressures (if high groundwater conditions are known to exist prior to obtaining soil boring data).
- (5) Identify requirements for protection of existing adjacent structure foundations that could be damaged during excavation.
- (6) Identify any material handling that is required (monorails, crane, davit, dock access, eyebolts) and approximate lifting capacities.
- (7) Identify major equipment and provide approximate weights (i.e., pumps, blowers, generators, engines).
- (8) Note any structural repairs required in existing buildings or any new or enlarged wall or floor openings. Note any concrete repairs or masonry rehabilitation and coordinate with client.
- (9) Identify design strength criteria for reinforced concrete and steel.

3.2.1.7 ***Mechanics***

- (1) For heating, ventilating, and air conditioning (HVAC) and other mechanical building systems, identify any special or specific expectations of the client.
- (2) Identify energy source(s) to be used for providing building heat (i.e., natural gas or electric) and supplier(s).
- (3) State method of providing heat to each structure, building, or section of building such as a lab or office area. Identify preliminary location of central heating and cooling facilities.
- (4) Identify ventilation method for each building and preliminary location of exhaust fans, louvers, air handling systems and ventilation rate criteria (air changes, cfm/ft², cfm/person).
- (5) Provide conceptual strategy for dealing with dust control, explosion resistance, fire protection, humidity control, emergency showers and/or eyewash, and hazard detection interlocks with ventilation. Describe equipment to be provided.
- (6) Identify mechanical building system requirements for generator and engine rooms (ventilation, combustion air, cooling system strategy, fuel system and storage, and drainage).
- (7) Identify areas to be air conditioned or de-humidified.

3.2.1.8 ***Electrical***

- (1) Provide any special or specific expectations of the client. Note any problems with existing equipment, if applicable, or certain manufacturer's equipment to be used or not used.
- (2) Identify power supply source.
- (3) Identify source and location of emergency power generator if required.
- (4) Provide general control descriptions that will be used to develop loop descriptions for automatic controls.
- (5) Complete an "Equipment and Controls Listing" as completely as possible.

- (6) Confirm instrumentation and control philosophy with the client (i.e., completely manual, data acquisition and logging with manual control, automated control of specific equipment or processes, or completely automated).
- (7) Identify work required at remote site from the project site (i.e., lift stations, well sites, booster stations, elevated tanks, other plants).
- (8) Identify equipment that is to be driven by variable speed systems.
- (9) Determine whether plant power distribution is to be overhead and/or underground.
- (10) Identify if existing lighting is to be revised with the client.
- (11) Identify method of providing outdoor lighting (i.e., high mast lights, pole-mounted street lights, or wall-mounted exterior building lights).
- (12) Identify whether Process and Instrumentation Diagram (P&ID) drawings are required and how many there will be.
- (13) Identify areas where electrical equipment including computers must be located in rooms with special temperature or humidity environments.
- (14) Identify pumps requiring seal water systems with solenoid valves, pressure switches, and controls for alarm/lockout.

3.2.2 Treatment Equipment. This stage of the preliminary design includes determining the system operating mode (i.e., manual or automatic), sizing the equipment, selecting materials of construction, determining an equipment layout, and upgrading the preliminary capital cost estimate to a $\pm 20\%$ accuracy. Key deliverable items include, but not limited to:

- (1) Schematic flow diagram (see Figure 3-2 for example)
- (2) Preliminary process equipment arrangement drawings (see Figure 3-3 for examples)
- (3) Outline specifications
- (4) Preliminary capital cost estimate.

3.2.2.1 Manual or Automatic Operation. AA fluoride removal systems can be operated either manually or automatically. In a manual operation, the treatment plant operator personally performs all of the operating functions and makes all operating decisions. The treatment plant equipment does not accomplish any function independent of the operating personnel. The equipment is simple and performs the basic functions that the operator implements. The manual operation includes the following:

- (1) Motors (pumps, chemical pumps, etc.) with manual start/stop controls. Some motors have manual speed adjustment capability. Chemical pumps have manual speed and stroke length adjustment capability.
- (2) Valves with manual handle, lever, handwheel, or chainwheel operators.
- (3) Instrumentation sensors with indicators. Instrumentation is installed in-line where operating data (flowrate, total flow, pressure, pH, and liquid levels) are indicated. In-line pH sensors, magmeters, ultrasonic level sensors are other instruments that require electric service.

In an automatic operation, the treatment plant is operated by a Programmable Logic Controller (PLC), which initially is programmed by the operator, the computer supplier, or an outside specialist. If programmed by someone other than the plant operator, the operator should be trained by that individual to adjust program variables and, if necessary, modify the program. The operator interface and printer are the

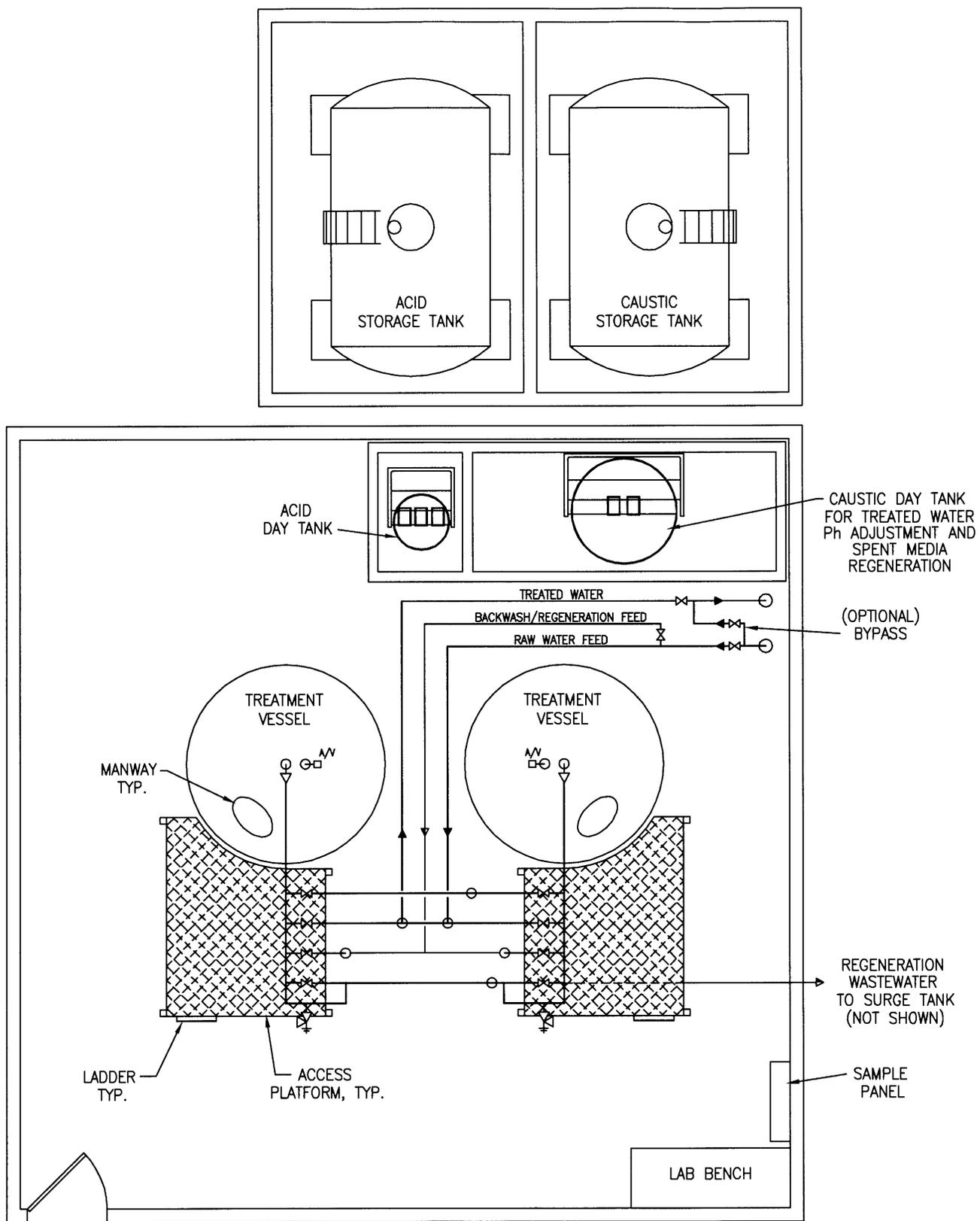


Figure 3-3. Treatment System Plan for an Activated Alumina Plant

equipment items the operator uses during the performance of treatment plant functions. In addition, the operator should calibrate and check all of the components of the automatic operating equipment system on a routine periodic basis. Finally, the treatment plant operator or a designated instrumentation and control specialist should be capable of performing emergency maintenance and/ or repair of all components.

Every function included in an automatic system should be capable of manual operation.

The automatic equipment is more sophisticated and costly than that used in a manual operation. When functioning normally, an automatic operation can function continuously with minimal operator attention. This is recommended for treatment systems in remote areas or areas that are difficult to access, and systems for which operator availability is limited. The automatic operation includes the following:

- (1) Motors for pumps, chemical pumps, air compressors, etc., are automatically turned on and off and may have speed adjustment controls. Chemical pumps may have a manual stroke length adjustment but can be paced by the flow and on/off operation of the plant.
- (2) Valves with either pneumatic/hydraulic or electric operation are required on the equipment. Valves require manual overrides during startup, power failure or compressed air failure. Valves should have opening and closing speed controls to prevent water hammer during automatic operation, especially on pump systems.
- (3) Automatic instrumentation may be electronic, pneumatic, or a combination of both. The instruments and controls should always be capable of transmitting and receiving electronic information to and from the PLC. In a fully automatic system all of the control, monitoring, and alarm functions are monitored and controlled by the PLC. Backup manual instruments (e.g., flowrate indicators, pressure indicators, pH indicators, and liquid level indicators) are recommended to provide verification of automatic instrumentation if treatment plant budget is available. Comprehensive automatic alarms that notify operators and/or shut down increments or the entire treatment system relating to every type of system malfunction at the moment such events occur is a necessary function that should be incorporated in all applicable instrumentation components.

A semiautomatic operation which employs individual controllers to automatically start/stop or adjust some, but not all, of the operational items in the system can contribute significantly to the treatment system operation without computer control of the entire operation. These semiautomatic functions should include alarms that will notify operators of process functions exceeding limits established for effective and/or safe operation. Alarm events can be staged at single (e.g., high) or dual (e.g., high-high) levels. In a dual-level alarm, the first level notifies the operator that the performance is out of tolerance, and the second level shuts down either a single process function (e.g., a pump) or the entire process. Examples of semiautomatic operational functions include, but are not limited to, the following:

- (1) Flow control loop includes an electronic flow sensor with totalizer (e.g., magnetic flowmeter) that sends an electronic signal to an electronic flow controller (with high and low flowrate alarms), which in turn sends an electronic signal to a flow control valve (butterfly valve or ball valve) with an actuator and electronic positioner. The plant operator designates the required flowrate at the flow controller. The controller receives the flowrate measurement from the flow sensor and transmits signals to the flow control valve positioner to adjust the valve position until the flowrate matches that required by the process. If the flowrate deviates from the limits established for the process, then a high flowrate or low flowrate alarm will be issued.

- (2) Pressure control loop includes an electronic pressure transmitter that sends an electronic signal to an electronic pressure controller (with high and low pressure alarms), which in turn sends an electronic signal to a pressure control valve with an actuator and electronic positioner. The plant operator designates the required pressure at the pressure controller. The controller receives the pressure measurement from the pressure transmitter and transmits signals to the pressure control valve positioner to adjust the valve position until the pressure matches that required by the process. If the pressure deviates from the limits established for the process, then a high pressure or low pressure alarm should be issued.
- (3) pH control loop includes an electronic pH sensor which transmits a pH signal to a pH analyzer (with high and low level alarms) which in turn sends an electronic signal to a converter which transmits a pulse signal to a chemical feed pump (acid or caustic) to adjust the feed pump stroke speed. The plant operator designates the required pH at the pH analyzer. The pH analyzer receives the pH measurement from the pH sensor and transmits signals to the chemical feed pump (via the converter) to adjust the pump stroke speed until the pH matches that required by the process. If the pH deviates from the limits established for the process, then a high pH or low pH alarm should be issued.
- (4) Liquid level control loop includes an electronic liquid level sensor (e.g., ultrasonic level sensor) which transmits an electronic liquid level signal to a level controller which indicates the liquid level and transmits an electronic signal to one or more motors (pump, mixer, etc.) to start or stop. At the level controller the plant operator designates the required liquid levels at which motors are to start and stop. The level controller receives the liquid level measurement from the liquid level sensor and transmits signals to the motor(s) to start or stop. If the liquid level deviates from the limits established for the process, then a high or low liquid level alarm should be issued.

Many other process functions are performed automatically by means of relays and other electrical devices. An example is the electrical interlock of chemical feed pumps with raw water pumps, which prevents chemical feed into the process without the flow of process water. Another example is the use of a flow switch in a pressure relief valve discharge pipe, which, upon detection of water flow, issues an alarm and stops the process feed pump. The list of individual failsafe automatic functions can be extensive. All applicable codes, standards, and OSHA requirements should be reviewed to determine which requirements are applicable to the project. Then based upon sound judgment, available budget, treatment plant operator capability, and availability, a decision should be made as to whether a given function should be automatic or manual.

3.2.2.2 Treatment Equipment Preliminary Design. This stage of the preliminary design encompasses sizing of equipment items and selecting materials of construction. An example with the use of dual vessels in parallel each with a conservative EBCT of 7.5 min in a downflow mode is provided in Appendix B (comparing this EBCT with the EBCTs of several existing AA plants on Table D-1, which range from 5.7 to 11.5 min). For automatic or semiautomatic operation the system basic design does not change; however, equipment material and installation costs will vary.

Media Bed and Vessel Design. In accordance with the discussion presented in Section 3.1.2, the recommended treatment concept is based on the use of two pressure vessels piped in parallel using the downflow treatment mode. Treatment vessel piping is configured to provide for media backwashing (upflow) and spent media regeneration. Materials of construction employed in the design example presented in Appendix B are carbon steel (grade selection based on cost-effective availability) that complies with American Society of Mechanical Engineers (ASME) Code Section VIII, Division 1. The interior of the vessels is lined with abrasion-resistant vinyl ester or epoxy coating. Interior lining material is NSF International-certified for potable water applications, and suitable for pH range 2.0-13.5. Vessel pressure

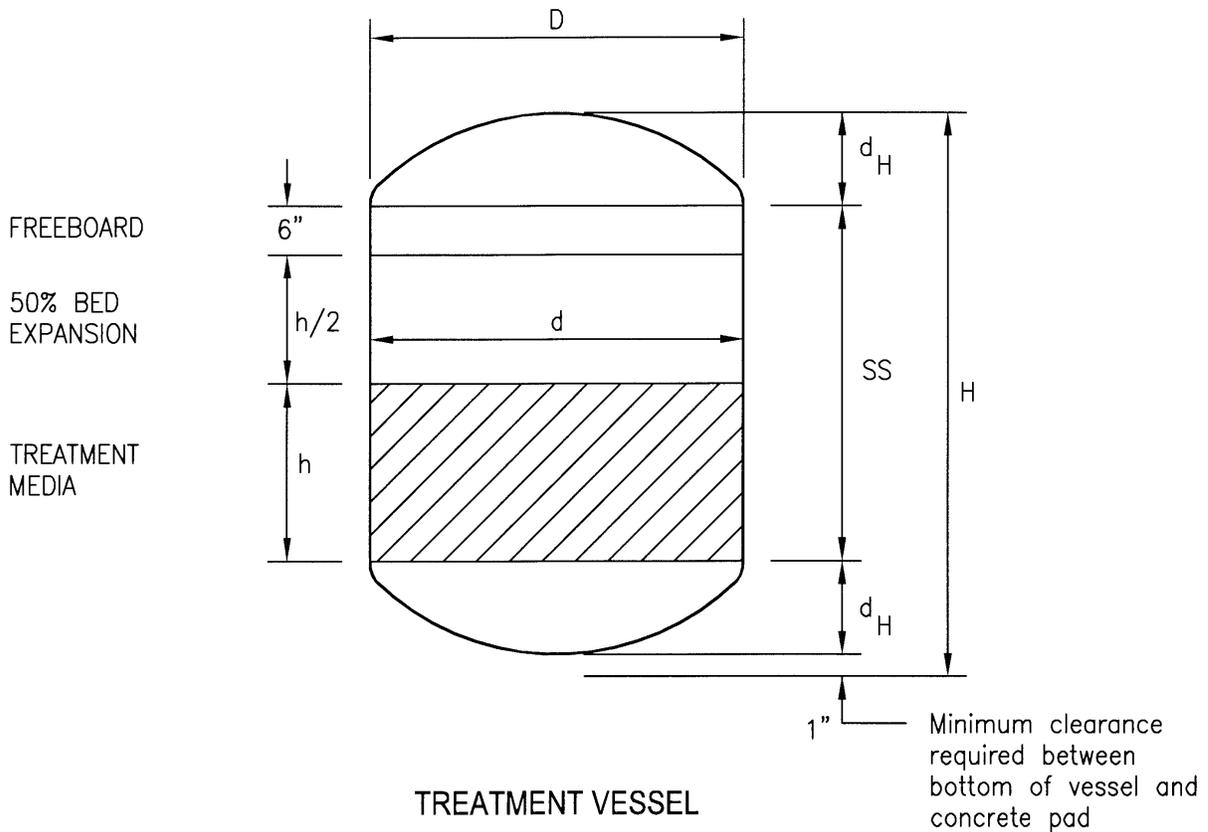
rating is 50 psig or the minimum necessary to satisfy system requirements. Other vessel materials of construction (e.g., fiberglass and fiber re-enforced plastic [FRB]), internal lining materials (e.g., abrasion resistant epoxy, rubber, etc.), and stainless steel without lining, may also be used.

Prior experience with AA indicates that the volume of the media (V) in each of the two parallel vessels is 1 ft³ per gpm of process water flowrate, which provides a conservative EBCT of 7.5 min. Actual residence time is approximately half the EBCT, because the space between the grains of media is approximately 50% of the total bed volume. When multiple beds are used, the volume of treatment media per unit is equal to the total treatment flowrate divided by the number of treatment beds (N). (Note: When raw water is bypassed and blended back with treated water, only the treated water is included in sizing the treatment media volume.) In order to prevent “wall effects”, bed diameter (d) should be equal to or greater than the bed depth (h). Good practice indicates that the bed depth should be a minimum of 3 ft and a maximum of 6 ft. At less than minimum depth, distribution problems may develop; and, at greater than maximum depth, fine material removal and pressure loss becomes a problem. For very small systems using tanks of 1-2 ft in diameter, the bed depths could be as low as 2 ft. A typical treatment bed and vessel design is illustrated in Figure 3-4. A summary of AA plant design and operation surveyed during the initial stage of this manual revision project is presented in Appendix C.

For fluoride removal, AA manufacturers commonly recommend a 5-min EBCT across each of two lead-lag beds (Reid, 2013). A more conservative EBCT of 7.5 min is also used to design adsorption vessels configured in series (Rubel, 1984). As the EBCT decreases below the recommended value, two undesirable outcomes may occur. First, the treatment is less efficient, resulting in treated water fluoride concentration not reaching a low enough concentration. Second, regeneration frequency increases, requiring more chemicals, operating cost, operator attention, and proportionately more downtime. Conversely, raising the EBCT above the recommended level increases the size of the treatment beds and their vessels, thereby increasing capital cost and space requirements.

Pressure vessel fabrication is standardized by diameter in multiples of 6-in outside diameter increments. Tooling for manufacture of pressure vessel dished heads is set up for that standard. Design dimensions differentiate between pressure vessel and treatment bed diameters. The vessel outside diameter (D) is approximately 1 in. greater than the bed (or vessel inside) diameter, which conservatively provides for both vessel walls with lining as well as fabrication tolerances. If the pressure is high (100 psig or greater), the 1 in. thickness will increase to reflect the increased vessel wall thickness.

Although many methods are available for distributing the water flow through a treatment bed, the following method has been successfully used in adsorptive media plants that are presently in operation. The water is piped downward into the vessel through an inlet diffuser. This diverts the flow into a horizontal pattern. From there it radiates in a horizontal plane prior to starting its downward flow through the adsorptive media bed. The bed, in turn, is supported by a false flat bottom, which is supported by the bottom head of the pressure vessel by means of concentric rings. The false flat bottom also supports the horizontal header and plastic fabric sleeved perforated lateral collection system. Treatment media are placed in the vessel through circular manway(s) with hinged cover(s) in the top head of the vessel.



SYMBOLS

- q – TREATED WATER FLOW RATE (gpm)
- d – TREATMENT BED DIAMETER (ft.), $d = \sqrt{4V/\pi h}$
- h – TREATMENT BED DEPTH (ft.)
- V – TREATMENT BED VOLUME – $\frac{\pi d^2 h}{4}$ (ft.³)
- M_d – DENSITY OF TREATMENT MEDIA (lb./ft.³)
- M_w – WEIGHT OF MEDIA (lbs.)
- D – OUTSIDE DIAMETER OF TREATMENT VESSEL (ft.)
- d_H – DEPTH OF DISHED PRESSURE HEAD (ft.)
- H – OVERALL HEIGHT OF SKID MOUNTED TREATMENT VESSEL (ft.)
- SS – STRAIGHT SIDE (ft.)

GIVEN

- $d > h/2, 3'-0" < h < 6'-0"$
- $H = 2 d_H + h + h/2 + 6" + 1"$
- $D = d + 1"$
- M_d = **48 lb/ft³** (VARIES WITH MEDIA IN VESSEL)
- M_w = m_d x v = +5V (lb.)

Figure 3-4. Treatment Bed and Vessel Design Calculations

Pipe Design. Because AA systems require process water pH adjustment and spent media regeneration, pipe material should be suitable for ambient temperature, pH range of 2.0 to 13.5, system pressure, and potable water service. At a low pH, carbon steel is not acceptable unless interior lining is included. Stainless steel is acceptable; however, it may be too costly. Plastic materials such as polyvinyl chloride (PVC), polypropylene, and high density polyethylene (HDPE) are satisfactory. PVC is usually the best selection based on its availability, NSF certification for potable water service, low cost, and ease of fabrication and assembly. The drawbacks to the PVC materials are their loss of strength at elevated temperatures (above 100°F); their coefficients of thermal expansion; their external support requirements; their deterioration from exposure to sunlight; and their vulnerabilities to damage from impact. Nevertheless, these liabilities are outweighed by the low cost and suitability for the service. The piping can easily be protected from all of the above concerns, except elevated ambient and/or water temperatures. If elevated temperature exists, the use of FRP pipe is recommended. This material provides the strength and support that is lacking in the pure plastic materials.

The piping system should be economically sized to allow for delivery of design flow without excessive pressure losses. If water velocities present conditions for water hammer (due to fast closing valves, etc.), shock-preventing devices should be provided.

Isolation and process control valves should be wafer style butterfly type, except in low flowrate systems where small pipe size dictates the use of true union ball valves. The use of inexpensive, easily maintained valves that operate manually provides minimum capital cost. The valves are automated by the inclusion of pneumatic or electric operators.

Pressure regulator and rate of flow control valves are recommended for safe operation of manually controlled treatment systems.

See Appendix B for pipe size design using the example employed for vessel and treatment media design.

Instrumentation Design. System functional requirements that are adapted to commercially available instruments should be specified. Included are:

Instrument	Range	Accuracy
1. Flow sensor (indicator/totalizer)	Varies ^(a)	±2%
2. Pressure indicator	Varies ^(a)	±1%
3. pH sensor/analyzer/alarm	0-14	±0.1
4. Level sensor/indicator	Varies ^(a)	±1%
5. Temperature indicator (optional)	30-120°F	±1%

(a) Range to be compatible with application, maximum measurement not to exceed 90% of range.

Acid Storage and Feed Subsystem. Acid feed and storage subsystems are included for pH adjustments of inlet water. The acid storage tank should be sized to contain tank truck bulk delivery quantities of concentrated sulfuric acid. For water systems that are not permitted to increase the sulfate concentration of the water, hydrochloric acid can be substituted. However, this acid is more costly, more difficult to handle, and results in highly corrosive treated water; therefore hydrochloric acid is not recommended. Bulk delivery provides the lowest unit price for the chemical. In small plants, acid consumption may not be enough to justify large volume purchase of chemicals. In the smaller plants, drums or even carboys may be more practical; therefore, for that type of operation, the requirement for a storage tank is eliminated. A 48,000-lb tank truck delivers 3,100 gal of 66°B° H₂SO₄ (15.5 lb/gal). A 5,000-gal tank

provides a 50% cushion. The example in Appendix B illustrates the method of designing the components of this system.

The sulfuric acid storage tank can be constructed of lined carbon steel or chlorinated polyvinyl chloride (CPVC). The storage tank should be protected from the elements and include a containment basin located outside of the treatment building. Typically, the containment basins are sized for 110% of the capacity of the storage tank. The 66°B' H₂SO₄ freezes at -20°F. Therefore, unless the treatment plant is located in an extremely cold climate, no freeze protection is required. All piping is to be 2-in. carbon steel with threaded cast iron fittings and plug valves. Elastomer seals, seats and gaskets should be Viton®.

The acid pumps are standard diaphragm models with materials of construction suitable for 66°B' H₂SO₄ service. Standard sulfuric acid service pumps should be specified. In the preliminary design, the sizing is determined by field test or theoretical calculation (see Appendix B). Acid feedrate varies with total alkalinity and free CO₂ content of the raw water. The feedrate is accurately determined experimentally by adjusting a raw water sample pH to 5.5 by acid titration. In a manual treatment plant operation, the operator should check the pH periodically and maintain it at 5.5. The pump stroke speed and length should be adjustable to accommodate these variations. An in-line static mixer should be installed immediately downstream of each acid injection point. This provides thorough mixing of the acid, which results in an accurate pH measurement by a pH sensor located at the discharge end of the mixer. The pH probes that are used to control pH should be calibrated against standard buffers at least once per week.

Immediately after spent media regeneration, an acid feed is required to lower pH of water for neutralization of a treatment bed prior to placing that bed back into treatment service. Neutralization pH is initially set at 2.5 and increases in steps until the treatment pH of 5.5 is achieved. A rinse step using the source or treated water can be included ahead of the neutralization step to remove residual fluoride and silica along with the dissolved alumina. Finally wastewater from the regeneration of an AA bed is collected in a surge tank where the pH is adjusted to near neutral. An additional acid feed pump is required to feed acid to the wastewater.

Caustic Soda Storage and Feed Subsystem. The caustic soda storage tank also is sized to contain tank truck bulk delivery quantities of 50% or 25% sodium hydroxide. A 48,000-lb tank truck delivers 3,850 gal of 50% NaOH which provides a 25% cushion in a 5,000-gal storage tank. 50% NaOH freezes at 55°F; 25% NaOH freezes at 0°F. Therefore, 50% NaOH, which is preferable because of price, requires heating to prevent freezing.

The caustic is used for treatment bed regeneration and pH adjustment of treated water. Regeneration frequency is a function of raw water fluoride concentration, flowrate and AA fluoride capacity. The amount of caustic required to neutralize the treated water, that is to raise the pH from 5.5 to the pH required for corrosion protection for the water system, is a function of the water chemistry at each installation. The actual caustic feedrate is easily determined experimentally by readjusting the treated water pH by titrating a sample with caustic until the desired pH is achieved. If a fraction of the raw water bypasses treatment and is blended with treated water, then the chemical required for pH adjustment is reduced.

In raw water with high alkalinity the lowering of pH produces high levels of dissolved CO₂. In those waters, removal of the CO₂ by aeration raises the pH (prior to blending), providing a less expensive treatment due to reduction of caustic required to raise the pH of the treated water. In low alkalinity water, the chemical addition is less expensive. The carbon steel caustic storage tank is covered in Appendix B. This vessel should be heat-treated to stress relieve welds. The carbon steel does not require an interior lining; however, it does require sandblasting and vacuum-cleaning prior to filling. All piping is to be 2-

inch carbon steel with threaded cast iron fittings and plug valves. Elastomer seals, slots and gaskets should be ethylene propylene diene monomer (EPDM).

Because 50% NaOH freezes at 55°F, it should maintain a minimum temperature of 70°F. This can be handled by a temperature-controlled electrical immersion heater. Insulated tanks with wall heaters are also available to store and heat the caustic soda. Twenty-five percent sodium hydroxide freezes at 0°F; therefore, unless it is located in an extremely cold climate, freeze protection is not required. The storage tank should be placed in a containment basin inside of an enclosure outside of the treatment building.

A pump is required to feed caustic into the effluent main through an in-line static mixer where the treated water is neutralized. For regeneration, a larger caustic feed pump is required for pumping the caustic through a static mixer in the regeneration feed pipe. There the caustic is diluted to the 1% (by weight) concentration required to regenerate the adsorptive treatment media.

Wastewater Lined Evaporation Pond. In the example used in Appendix B, it is assumed that the most cost-effectively and preferred wastewater disposal option is a lined evaporation pond. This method, however, can be used only in arid regions in the desert southwest. It is not a viable method in the humid southeast or cold climate of the northern tier of states. In those areas a viable disposal option is to neutralize the regeneration wastewater with acid as it leaves the treatment vessel and collect the entire regeneration wastewater batch in a surge tank. The neutralized wastewater is then bled at a controlled flowrate to the sanitary sewer. In the sewer, it blends with the defluorinated water that has been discharged to waste.

To size the lined evaporation pond, the basic information required is the average annual volume of regeneration wastewater to be evaporated and the average annual evaporation rate. The former can be estimated and the latter can be obtained from the national weather bureau. The treatment plant production is normally much higher in summer than winter, and evaporation rate is also higher in summer. The ponds have sloped sides, pond depth to be 8ft minimum. Ponds are to be lined with 30 mil reinforced hypalon, a material that is not vulnerable to ultraviolet radiation deterioration or exposure to pH 12. The dissolved solids will concentrate and precipitate in the pond.

3.2.3 Preliminary Treatment Equipment Arrangement. Once all of the major equipment size and configuration information is available, a layout (arrangement drawing) is prepared. The layout provides sufficient space for proper installation, operation and maintenance for the treatment system as well as each individual equipment item. OSHA standards should be applied to these decisions during the equipment arrangement design stage. These requirements may be supplemented or superseded by state or local health and safety regulations, or, in some cases, insurance regulations. A compact arrangement to minimize space and resulting cost requirements is recommended. Figure 3-3 illustrates typical preliminary arrangement plans. These arrangements provide no frills, but do include ample space for ease of operation and maintenance. Easy access to all valves and instruments reduces plant operator effort.

The type of building used to protect the treatment system (and operator) from the elements depends on the climate. Standard pre-engineered steel buildings are low-cost, modular units. Concrete block or other material also may be used. Standard building dimensions that satisfy the installation, operation, and maintenance space requirements for the treatment system should be selected. The building should provide access doors, lighting, ventilation, emergency shower and eye wash, and a laboratory bench with sink. All other features are optional.

When the arrangement is completed, the preliminary cost estimate is prepared.

Manual operation is the method employed in the design example in Appendix B. The basic process requirements should be reviewed at each stage of design to assure that every item required to operate the process is included. Although detail design occurs during the final design phase, provision for operator access for every equipment item should be provided. Automatic operation does not require total accessibility; access for maintenance functions for which ladder or scaffold access will suffice. The extra equipment items required solely for automatic operation (including but not limited to PLC, and operator, interface) occupy minimal space and are located in positions that are most accessible to the operator.

3.2.4 Preliminary Cost Estimate. At completion of the preliminary design, the preliminary cost estimate is prepared based upon the equipment that has been selected, the equipment arrangement and the building selection. This estimate should be based on the material equipment quantities, unit prices to labor and material, and finally summarized in a format that is preferred by the owner. This estimate should have an accuracy of $\pm 20\%$. To assure sufficient budget for the project, it is prudent to estimate on the high side at this stage of design. This may be accomplished by means of a contingency to cover unforeseen costs, and an inflation escalation factor.

3.2.5 Preliminary Design Revisions. The preliminary design package (described above) then is submitted for approval prior to proceeding with the final design. This package may require the approval of regulatory authorities, as well as the owner. Requested acceptable changes should be incorporated and resubmit for approval. Once all requested changes are implemented and preliminary design approval is received, the final design can proceed.

3.3 Final Design

After completion and approval of the preliminary design by the client, the final design proceeds. This includes detail design of all of the process equipment and piping, complete process system analysis, complete detail design of the building including site work, and a final capital cost estimate accurate to within 10%. The deliverable items are:

- (1) Complete set of construction plans and specifications
- (2) Final capital cost estimate.

The final design starts with the treatment system equipment (if applicable, including the wastewater surge tank); continues with the building (including concrete slabs and foundations, earthwork excavation/back-fill/compaction, heating, cooling, painting, lighting, utilities, laboratory, personnel facilities, etc.); and finishes with the site work (including utilities, drainage, paving and landscaping). The latter items apply to every type of treatment plant; although they are integral with the treatment system, they are not addressed in this manual. The only portions of the final design that should be addressed are the pertinent aspects of the treatment equipment which were not covered in the preliminary design. During the conceptual design and preliminary design, the basic equipment that accomplishes the required functions were selected, sized, and arranged in a compact, efficient layout. The decision was cost-conscious, using minimum sizes (or standard sizes) and the least expensive materials that satisfied the service and/or environment. However, in the final design, this effort can be defeated by not heeding simple basic cost control principles. Some of these are:

- (1) Minimize detail (e.g., pipe supports—use one style, one material, and components common to all sizes).
- (2) Minimize the number of bends in pipe runs (some bends are necessary—those that are optional only increase costs).

- (3) Minimize field labor; shop fabricate where possible (e.g., access platforms and pipe supports can be mounted on brackets that are shop fabricated on vessel).
- (4) Skid-mount major equipment items (skids distribute weight of vessels over small mat foundations in place of piers and spread footings, thereby costly foundation work is eliminated).
- (5) Use treatment vessels as a heat sink to provide insulated building cooling or heating or both (eliminates heating and/or cooling equipment in addition to reducing energy cost). Consideration must be given, however, to humid climates where cold tanks will result in sweating problems.
- (6) Simplify everything.

All subsystems should be analyzed (refer to schematic flow diagrams in Figure 3-2) to account for all components in both equipment specifications and installation drawings. The specifications and drawings should provide all information necessary to fabricate and install the equipment. Extra effort to eliminate ambiguity in detail and/or specified requirements should be exercised. All items should be satisfactory for service conditions besides being able to perform required functions. Each item should be easy to maintain; spare parts necessary for continuous operation should be included with the original equipment. All tools required for initial startup as well as operation and maintenance should be furnished during the construction phase of the project. After all components in each of the subsystems have been selected, hydraulic analysis should be made to determine velocities and pressure drops through the system. Calculations should be run for normal treatment flow and backwash flow. The latter is more severe, but of short duration. If pressure losses are excessive, the design should be modified by decreasing or eliminating losses (e.g., increase pipe size, eliminate bends or restrictions, etc.).

Upon completion of system installation, functional checkout requirements should be accomplished. All piping should be cleaned and pressure tested prior to startup. All leaks should be corrected and retested. Recommended test pressure is 150% of design pressure. Potable water piping and vessels should be disinfected prior to startup. Disinfection procedures should be in compliance with regulatory agency requirements and material manufacturer's disinfection requirements/limitations. All electrical systems should satisfy a functional checkout. All instruments should be calibrated; if accuracy does not meet requirements stated under instrumentation design in Section 3.2.2.2, the instruments are to be replaced. When the plant operation begins, a check on actual system pressure drop is required. If there is a discrepancy between design and actual pressure drop, the cause should be determined (obstruction in line, faulty valve, installation error, design error, etc.) and rectified. Pressure relief valves should be tested; if not accurate, they should be adjusted or replaced. Although this activity takes place during treatment plant startup, it should be incorporated as a construction document requirement.

3.3.1 Treatment Equipment Final Design

3.3.1.1 Treatment Bed and Vessel Design. The required AA media volume is determined by bed dimensions and resulting weight in the preliminary design. It is recommended that a minimum of 10% extra media be ordered. For lowest price and ease of handling, the media should be ordered in fiber drums (approximately 5 to 8 ft³) on pallets or in supersacks (approximately 40 ft³ per supersack). The media should be NSF-certified for potable water application and demonstrate fluoride removal capacity. The commonly available AA products on the market include Alcan 400G and Alcoa CPN.

Each media vessel should have a support system to transfer its loaded weight to the foundation and ultimately to the soil. The loaded weight includes the media, the water, attached appurtenances (platform, pipe filled with liquid, etc.), the vessel, and applicable seismic and/or wind loads. The support legs

should be as short as possible to reduce head room requirements as well as cost. If the equipment is skid-mounted, the vessel legs should be integral with the skid to distribute the weight over an area greater than the dimension of the vessel. This distribution eliminates point loads of vessel support legs, so costly piers, footings, and excavation requirements are eliminated. The skid should have provisions for anchorage to the foundation. Exterior brackets (if uniform and simply detailed) are not costly and provide supports that eliminate need for cumbersome costly field fabrications. Conversely, interior brackets, though required to anchor (or support) vessel internal distribution or collection systems, should be held to a bare minimum because they are costly to line. Epoxy (or rubber) linings with abrasion resistance qualities are recommended. Vessel interior lining should extend through vessel opening out to the outside edge of flange faces. Alternatively, vessels may be constructed of stainless steel (no lining required). Openings in the vessels should be limited to the following:

- (1) Influent pipe – enters vertically at center of top head.
- (2) Effluent pipe – exits horizontally through vertical straight side immediately above false flat bottom in front of vessel, or vertically at the center of the bottom head.
- (3) Air/vacuum valve (vent) – mounts vertically on top head adjacent to influent pipe.
- (4) Media removal – exits horizontally through vertical straight side immediately above false flat bottom at orientation assigned to this function. Some AA plants do not remove media, which attrites due to backwash and regeneration. These plants routinely top off the vessels with virgin AA.
- (5) Manway – 16-in diameter (minimum) mounted on top head with center line located within 3 ft of center of vessel and oriented toward work platform. Manway cover to be hinged or davited.

It is recommended that pad flanges be used for pipe openings in place of nozzles. Pad flanges are flanges that are integral with the tank wall. The exterior faces are drilled and tapped for threaded studs. The pad flanges save the cost of material and labor, and are much easier to line; they also reduce the dimensional requirements of the vessel. The vessel also requires lifting lugs suitable for handling the weight of the empty vessel during installation. Once installed, the vessel should be shimmed and leveled. All space between the bottom surface of the skid structure and the foundation should be sealed with an expansion-type grout; provisions should be included to drain the area under the vessel.

The type of vessel internal distribution and collection piping used in operational fluoride removal plants is defined in the preliminary design. Because there are many acceptable vessel internal design concepts, configuration details are left to sound engineering judgment. The main points to consider in the design are as follows:

- (1) Maintain uniform distribution
- (2) Provide minimum pressure drop through internal piping (but sufficient to assure uniform distribution)
- (3) Prevent wall effects and channeling
- (4) Collect treated water within 2 in. of bottom of treatment bed
- (5) Anchor internal piping components to vessel to prevent any horizontal or vertical movement during operation
- (6) Ensure that construction materials are suitable for pH range of 2.0 to 13.5 (PVC, stainless steel are acceptable).

Underdrain failures create significant problems; treatment media loss, service disruption and labor to repair problems are very costly. A service platform with access ladder or a roof hatch is required for use in loading AA media into the vessel. Handrail, toe plate, and other OSHA-required features should be included.

3.3.1.2 Pipe Design. Each piping subsystem should be reviewed to select each of the subsystem components. Exclusive of the chemical subsystem, five piping subsystems and two optional subsystems are listed in the general plan; they are:

- (1) Raw water influent main
- (2) Intervessel pipe manifold
- (3) Treated water effluent main
- (4) Raw water bypass main
- (5) Backwash regeneration feed main (optional)
- (6) Wastewater main
- (7) Sample panel (optional).

The detail design now proceeds for each of those subsystems. First, the equipment specification for each equipment component in each subsystem should be defined. This is followed by a detailed installation drawing, which locates each component and provides access for operation and maintenance. As each subsystem nears completion, provisions for pipe system support and anchorage, as well as for thermal expansion/contraction, should be incorporated in the detail design.

The interface where the concentrated chemical and treatment unit branch piping join is designated as a chemical injector detail. The chemical injector detail should include provisions to protect materials of construction from the heat of dilution of concentrated corrosive chemicals. The key factor is to prevent flow of concentrated chemical when raw water (dilution water) is not flowing. The dilution water should dissipate the heat. The actual injection should take place in the center of the raw water pipe through an injector that extends from the concentrated chemical pipe. The injector material should be capable of withstanding the high heat of dilution that develops specifically with sulfuric acid and to a lesser degree with caustic soda. Type 316 stainless steel and Teflon[®] are satisfactory. It also is very important that the concentrated chemical be injected upward from below; otherwise concentrated chemicals with specific gravities greater than that of water will seep by gravity into the raw water when flow stops. As described previously, the chemical pumps are to be de-energized when the well pump (or other feed pump) is not running.

The treated water pH should be monitored carefully. A pH sensor installed in the treated water main indicates the pH at an analyzer. This analyzer should be equipped with adjustable high and low level pH alarms. The alarms should be interlocked with the well pump (or other feed pump) control (magnetic starter), shutting it down when out-of-tolerance pH excursions occur. A visual and/or audio alarm should be initiated to notify the operator regarding the event.

A chemical injector detail similar to that used for acid in the treatment unit branch piping should be used in the treated water main to inject caustic in order to raise pH in the treated water. If aeration for removal of CO₂ is used in place of or in combination with caustic soda injection for raising treated water pH, then system pressure will be dissipated and the treated water will be repressurized. If the water utility has ground level storage tanks, the aeration-neutralization concept can be accomplished without the need for a clearwell and repressurization. The aerator can be installed at an elevation that will permit the neutralized treated water to flow to storage via gravity.

Easy maintenance is an important feature in all piping systems. Air bleed valves should be installed at all high points; drain valves should be installed at all low points. This assists the plant operator in both filling and draining pipe systems. Air/vacuum valve and pressure relief valve discharges are to be piped to drains. This feature satisfies both operator safety and housekeeping requirements. Bypass piping for flow control, pressure control, flowmeter, and other in-line mechanical accessories is optional. Individual equipment item bypass piping is costly and requires extra space. However, if continuous treatment plant operation is mandatory, bypass piping should be included.

3.3.1.3 Instrument Design. Ease of maintenance is very important. Instruments require periodic calibration and/or maintenance. Temperature indicators (optional) require thermal wells installed permanently in the pipe. Pressure indicators require gauge cocks to shut off flow in the branch to the instrument. pH sensing probes require isolation valves and union type mounting connections (avoids twisting of signal cables). Supply of pH standard buffers (4.0, 7.0, and 10.0) should be specified for pH instrument calibration. A laboratory bench should be located adjacent to the sample panel. The sample panel receives flow directly from sample points located in the process piping. The sample panel consists of a manifold of PVC or polyethylene tubing with shutoff valves, which allows the plant operator to draw samples from any point in the process at the laboratory bench. Laboratory equipment should be specified to include wall cabinet, base cabinet with chemical resistant counter top and integral sink, 115V/1N/60Hz 20-amp duplex receptacle, laboratory equipment/glassware/reagents for analysis of pH, arsenic, and other ions. A deionized water capability for cleaning glassware and dilution of samples should be included.

3.3.1.4 Acid Storage and Feed Subsystem. Operator safety for work within close proximity of highly corrosive chemicals takes priority over process functional requirements. Emergency shower and eyewash *must* be located within 20 ft of any work area at which operator exposure to acid or caustic soda exists. Protective clothing should be specified. Neutralization materials (e.g., sodium carbonate) should be provided to handle spills. Potential spill areas must be physically contained. Containment volumes should be sufficient to completely retain maximum spillage.

Chemical bulk storage tanks are covered in the preliminary design.

To minimize corrosion of acid pipe material, acid flowrate is recommended to be less than 0.1 ft/sec. Threaded pipe and fittings are not recommended; tubing and Swagelok fittings are recommended. CPVC or Teflon® are satisfactory except for their vulnerability to damage from external impact forces. Therefore protective clear reinforced plastic tubing completely containing the plastic chemical lines is recommended. The use of double containment piping systems can also be considered. Positive backflow prevention should be incorporated in each chemical feed line. Day tanks should be vented to the atmosphere, have a valved drain, and have a fill line float valve for failsafe backup control to prevent overflow. For treatment systems that use HCl instead of H₂SO₄ for pH adjustment, it is recommended that references on materials acceptable for the handling and storing of this acid be consulted.

One acid feed pump is required for influent water pH adjustment. Acid feed pumps are also required to adjust pH during neutralization following a regeneration, and to neutralize regeneration wastewater in the wastewater surge tank. Though preferable to use separate pumps for each function, it is feasible to accomplish all three functions with a single pump. The pump should be sized for a minimum of 110% of the maximum flowrate that it will provide; it should have a turndown limit no greater than 50% of the minimum required flow. Acid pump power should be interlocked with the well pump (or other feed pump) so that the acid pump is de-energized when that pump is not running. If the chemical feed pump is mounted above the day tank, a foot valve is required in the suction tube. Antisiphon provisions should be included in the system. Because considerably more acid (approximately 1 gal/ft³ of activated alumina) is consumed during the regeneration of an activated alumina bed than during routine treatment operation, a day tank will need to be refilled several times during the neutralization phase of the regeneration. The

day tank should be sized for a minimum of 200% of the daily acid consumption for the treatment process pH adjustment requirement. The day tank should be translucent with gallon calibration on the tank wall. The day tank should be set in an open-top, acid-resistant containment basin. All relevant regulatory authorities should be consulted to ensure compliance with all safety regulations.

3.3.1.5 Caustic Soda Storage and Feed System. The safety requirements stated for acid also apply to caustic soda. Vinegar should be provided to neutralize caustic spills.

The day tank and pump design features recommended for acid systems also apply to caustic. Two caustic pumps and day tanks are required. The process pH adjustment pump should be sized to pump 110% of the maximum process required. The rule of thumb for sizing the caustic soda regeneration feed pump requires provisions of 2 gal of 50% NaOH/ft³ of activated alumina for activated alumina systems per hour. Depending upon the size of the system, a centrifugal pump or an air-operated diaphragm pump are feed pump options. The process pH adjustment day tank should be sized for 200% of the maximum daily consumption. The regeneration day tank should be the next standard tank size greater than the requirement for one regeneration. Both tanks can be set in one containment basin, sized for the largest tank. Alternatively, a common day tank can be sized appropriately and utilized for both process pH adjustment and regeneration; this is more cost effective due to the cost of day tanks with heat trace installed. The regeneration pump can be calibrated by means of timing the flow and adjusting as necessary to arrive at the design flowrate. Carbon steel threaded pipe or PVC pipe is suitable for the service. All relevant regulatory authorities should be consulted to ensure compliance with all safety regulations.

3.3.1.6 Regeneration Wastewater Surge Tank. Although treatment and disposal of regeneration wastewater are not included in this design manual, a surge tank to receive the wastewater is indicated. The wastewater surge tank should receive the entire batch of regeneration wastewater from the start of backwash to the completion of treatment bed neutralization. To provide adequate capacity for containment of the entire batch of regeneration wastewater, this tank should be sized to contain 400 gal/ft³ for AA systems. This tank can be either a ground-level atmospheric tank or a tank positioned below the discharge point of the vessels to allow for gravity-transferring of portion of the waste stream. The tank is constructed of carbon steel or PVC and should include a carbon steel floor and roof and an interior epoxy lining. The tank should include a reinforced concrete containment structure. The tank should include fill, chemical feed, drain overflow vent, multiple discharge, and multiple sample pipe connections. The tank should include one ground-level manway and one roof manway (with safety ladder and handrails), provisions for a liquid level indicator, for an ultrasonic liquid sludge level sensor, liquid level controller, and a side entry mixer.

3.3.2 Final Drawings. All of the information required for complete installation of a fluoride removal plant should appear in the final construction drawings and specification package. Isometric drawings for clarification of piping subsystems are recommended; these views clarify the assembly for the installer (see Figure 3-5). Cross-referencing drawings, notes, and specifications also is recommended.

3.3.3 Final Capital Cost Estimate. Similar to the preparation of the preliminary cost estimate, the final cost estimate is prepared based on a take off of the installed system. The estimate is now based upon exact detailed information rather than general information which was used during the preliminary estimate. The estimate is presented in the same format and is to be accurate within $\pm 10\%$. Because financial commitments are determined at this stage, this degree of accuracy is required.

3.3.4 Final Design Revisions. Upon their completion, the final construction drawings and specifications are submitted for approval to the owner and the regulatory authorities. If changes or addi-

tional requirements are requested, they should be incorporated and resubmitted for approval. If communication with the approving parties has taken place during the course of the design, then time-consuming resubmittals should not be necessary. Upon receipt of approval, the owner, with assistance from the engineer, solicits bids for the construction of the arsenic removal water treatment plant.

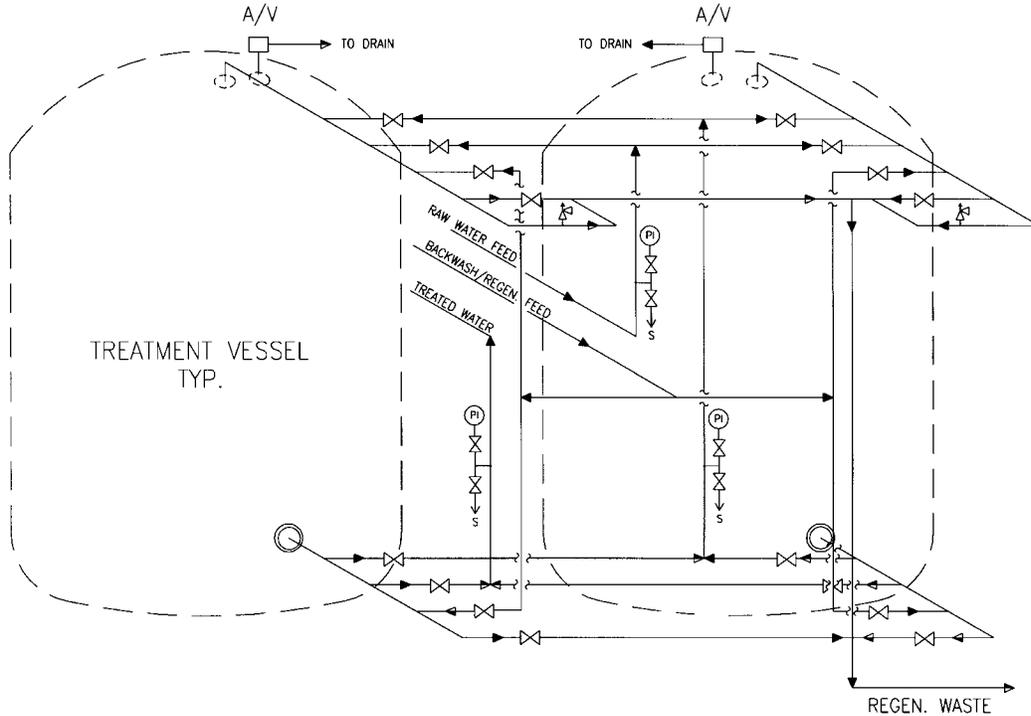


Figure 3-5. Treatment Vessels Piping Isometric

4.0: ACTIVATED ALUMINA PLANT OPERATION

4.1 Introduction

Upon completion and approval of the final design plans, the owner (client) proceeds to advertise for bids for construction of the treatment plant. The construction contract normally is awarded to the firm submitting the lowest bid. Occasionally, circumstances arise that disqualify the low bidder, in which case the lowest qualified bidder is awarded the contract. Upon award of the construction contract, the engineer may be requested to supervise the work of the construction contractor. This responsibility may be limited to periodic visits to the site to assure the client that the general intent of the design is being fulfilled; or it may include day-to-day inspection and approval of the work as it is being performed. The engineer should review and approve all shop drawings and other information submitted by the contractor and/or subcontractors and material suppliers. All acceptable substitutions should be approved in writing by the engineer. Upon completion of the construction phase of the project, the engineer normally is requested to perform a final inspection. This entails a formal approval indicating to the owner that all installed items are in compliance with the requirements of the design. Any corrective work required at that time is covered by a punch list and/or warranty. The warranty period (normally one year) commences upon final acceptance of the project by the owner from the contractor. Final acceptance usually takes place upon completion of all major punch list items.

Preparation for treatment plant startup and operator training may or may not be included in the construction contract. Although this area of contract responsibility is not germane to this manual, the activities and events that lead up to routine operation are. This chapter discusses those steps in the sense that the operator is performing them. The operator could be the contractor, the owner's representative, or an independent third party.

System operating supplies, including treatment chemicals, laboratory supplies, and recommended spare parts should be procured, and stored on site. The treatment plant operating and maintenance instructions (O&M manual) should be available at the project site. Included in the O&M manual are the valve number diagram which corresponds to brass tags on the valves (see Figure 4-1), a valve directory furnished by the contractor, and a valve operation chart (see Table 4-1).

The media vessels and piping should be disinfected in accordance with AWWA standard procedures. Activated alumina then is placed in the vessels. After backwashing to remove fines, the AA plant is ready to start operation.

There are four basic modes of operation: treatment, backwash, regeneration, and acid neutralization. Operating details for each of these modes are covered in this section. It is important to note that each of the above modes uses raw water during the operation.

4.2 Initial System Startup

The operator should thoroughly review the O&M manual, become familiarized with every component of the plant, and resolve any questions that arise.

Proper placement of AA in a treatment vessel is critical to future system performance. Dry media usually is delivered in drums or sacks. The media volume is determined on a dry weight basis. The actual density varies with the degree of packing of the bed. Unless instructed otherwise by the manufacturer, 48 lb/ft³ is a suggested media density for use in weight calculations for AA. The virgin granular AA material is "coated" with caustic. During media loading, a small amount of fines can become airborne

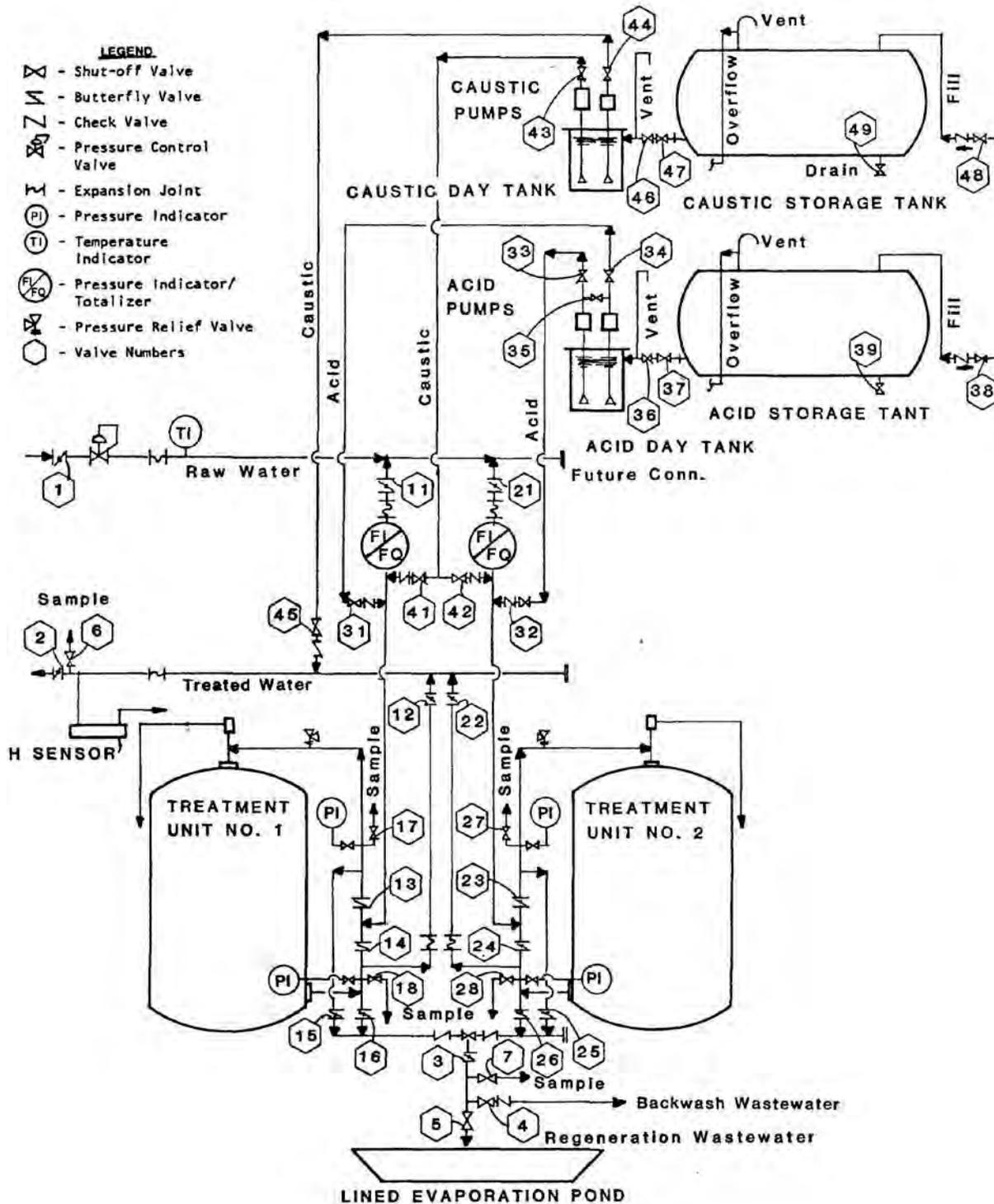


Figure 4-1. An Example Valve Number Diagram

Table 4-1. An Example Valve Operation Chart for Treatment Vessels in Media Regeneration Modes^(a)

Function			Valve Numbers																				Chemical Shutoff										
	Unit No. 1 Operation	Unit No. 2 Operation	1		2		3		4		5		6		7		17		18		27			28		31		32		41		42	
Unit No. 1	Unit No. 2		11	12	13	14	15	16	21	22	23	24	25	26	1	2	3	4	5	6	7	17	18	27	28	31	32	41	42	43			
Treatment	Treatment		0	0	0	X	X	X	0	0	0	X	X	X	0	0	X	X	X	P	X	P	P	P	P	0	0	X	X	0			
Drain	Treatment		X	X	X	X	X	0	0	0	0	X	X	X	0	0	0	0	X	X	X	X	X	P	P	X	0	X	X	0			
Backwash	Shutoff		0	X	X	0	0	X	X	X	0	X	X	X	0	0	0	0	X	X	0	X	X	X	X	X	X	X	X	X			
Drain	Treatment		X	X	X	X	X	0	0	0	0	X	X	X	0	0	0	0	X	X	X	X	X	X	X	X	0	X	X	0			
Upflow Regen.	Treatment		0	X	X	0	0	X	0	0	0	X	X	X	0	0	0	X	0	X	P	X	X	X	X	X	0	0	X	0			
Upflow Rinse	Treatment		0	X	X	0	0	X	0	0	0	X	X	X	0	0	0	X	0	X	X	X	X	X	X	X	0	X	X	0			
Drain	Treatment		X	X	X	X	X	0	0	0	0	X	X	X	0	0	0	X	0	X	X	X	X	X	X	X	0	X	X	0			
Downflow Regen.	Treatment		0	X	0	X	X	0	0	0	0	X	X	X	0	0	0	X	0	X	P	X	X	X	X	X	0	0	X	0			
Drain	Treatment		X	X	X	X	X	0	0	0	0	X	X	X	0	0	0	X	0	X	X	X	X	X	X	X	0	X	X	0			
Neutralization	Treatment		0	X	0	X	X	0	0	0	0	X	X	X	0	0	0	X	0	X	P	0	P	X	X	0	0	X	X	0			
Treatment	Treatment		0	0	0	X	X	X	0	0	0	X	X	X	0	0	X	X	X	P	X	P	P	P	P	0	0	X	X	0			
Treatment	Drain		0	0	0	X	X	X	X	X	X	X	X	0	0	0	0	X	X	P	X	P	P	X	X	0	X	X	0				
Shutoff	Backwash		X	X	0	X	X	X	0	X	X	0	0	X	0	0	0	0	X	X	0	X	X	X	X	X	X	X	X	X			
Treatment	Drain		0	0	0	X	X	X	X	X	X	X	X	0	0	0	0	X	X	X	X	X	X	X	X	0	X	X	X				
Treatment	Upflow Regen.		0	0	0	X	X	X	0	X	X	0	0	X	0	0	0	X	0	X	P	X	X	X	X	0	X	X	0	0			
Treatment	Upflow Rinse		0	0	0	X	X	X	0	X	X	0	0	X	0	0	0	X	0	X	P	X	X	X	X	0	X	X	X	0			
Treatment	Drain		0	0	0	X	X	X	X	X	X	X	X	0	0	0	0	X	0	X	X	X	X	X	X	0	X	X	X				
Treatment	Downflow Regen.		0	0	0	X	X	X	0	X	0	X	X	0	0	0	0	X	0	X	P	X	X	X	X	0	X	X	0				
Treatment	Drain		0	0	0	X	X	X	X	X	X	X	X	0	0	0	0	X	0	X	X	X	X	X	X	0	X	X	X				
Treatment	Neutralization		0	0	0	X	X	X	0	X	0	X	X	0	0	0	0	X	0	X	P	X	X	0	P	0	0	X	X				
Treatment	Treatment		0	0	0	X	X	X	0	0	0	X	X	0	0	X	X	X	P	X	P	P	P	P	P	0	0	X	X	0			

Legend: 0 - Valve Open
 X - Valve Closed
 P - Periodic Sample

(a) Refer to Figure 4-1 for valve location.

and are irritating to the personnel who are handling them. Eye, skin, and inhalation protection are recommended during vessel loading activity.

The vessel should be half-filled with water prior to placing underbed materials and AA media through a manway in the top of the vessel. Upon placing AA into the vessel, heat is generated by the wetting of the caustic “coating” on the alumina grains. The water in the tank dissipates the heat, thereby preventing cementing of the bed. The water in the vessel also separates fines from granular materials, protects the underdrain assembly from impact, and initiates stratification of the bed. It is recommended that the bed be placed in two or three lifts. In a two- or multiple-bed treatment system, alternate placing of media and backwashing can be worked together among the treatment units. The beds should be thoroughly backwashed with raw water after each lift. The backwash flowrate should be adjusted to provide 30% to 50% bed expansion, which is typically 9 gpm/ft² or higher. For extremely warm or cold water, backwash flowrates may have to be adjusted up or down, respectively. To remove all media fines from the bed, each backwash should last for at least 30 min. If the fines remain in the beds, potential problems such as channeling, excessive pressure drop, or even cementing can develop. The extra backwashing effort during bed placement permits fines at the bottom of the beds to work their way up and out to waste. Because the lower portions of the beds (which contain the largest particles) do not expand during backwash, fines not backwashed out of the bed at that stage may be permanently locked into the beds. The backwash wastewater should be directed to waste.

To accurately estimate the bed depth in each vessel, it is recommended that freeboard be measured after the placement of the underbed materials and after the placement, backwashing, and downflow rinse of the AA media. The downflow rinse helps settle a freshly backwashed bed. The freeboard is measured using a tape measure from the top of the underbed materials or the AA bed to a set point on the manway used to load the materials. The difference of the measurements is the bed depth, which can be used to calculate the bed volume and confirm if sufficient media has been placed into the vessel.

The pressure loss checkout mentioned in Section 3.3, final design, should be accomplished at this point. Table 4-2 presents calculated pressure drop through the AA media. If there is a pressure loss problem, it should be corrected prior to system startup.

**Table 4-2. Calculated Activated Alumina (28×48 Mesh)
Downflow Pressure Drop Data**

Water Flowrate (gpm/ft²)	Pressure Drop in psi per Foot of Bed Depth	Modified Reynolds Number
2.0	0.009	2375
3.0	0.018	3555
4.0	0.028	4735
5.0	0.040	5900
6.0	0.053	7111
7.0	0.068	8291

The acid and base used for pH adjustment should now be placed in or carefully transferred to the designed containers. The online pH meters should be calibrated. For AA, the optimum pH values are in the range of 5.0-6.0. Because acid feedrates are a function of raw water alkalinity, they vary from one water to another. When the alkalinity of the raw water is extremely high or the cost of acid is very high, it can be more cost-effective to operate in a pH range of 6.0 to 6.5 to reduce the acid consumption (even though fluoride removal efficiency is also reduced).

Before system startup, the plant should be cleaned up. Airborne fines that form a dust-like coating on piping and equipment should be removed. Good housekeeping should begin immediately and be continued on a permanent basis.

4.3 System Operations

4.3.1 Treatment Mode. The downflow treatment for the virgin run can now begin. It is recommended that one vessel be placed in operation at a time. This will allow the operator to concentrate on initial raw water pH adjustment on one treatment unit until it is in stable operation; the operator then can devote his/her full attention to the second treatment unit. The basic operating mode flow schematic is illustrated in Figure 4-2.

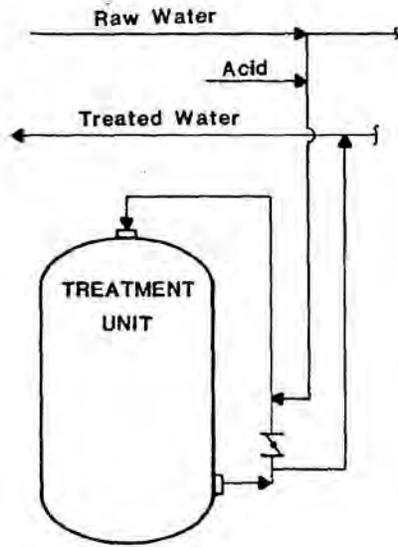
With AA, the initial effluent pH is high with no fluoride removal. After a short period, both pH and fluoride in the treated water drop to anticipated levels. At that time, the treated water can be directed to storage and/or distribution. The freshly installed media can also be neutralized with sulfuric acid similar to the final step of acid neutralization prior to putting back the vessels into service following media regeneration. Depending on the requirements of the state or local regulatory authorities, samples may have to be analyzed at a certified testing laboratory prior to approval of treated water entering the distribution system.

In the parallel operation utilizing two treatment vessels, the fluoride removal process takes place in a treatment band (or adsorption zone) contained in each of the two vessels. After a treatment period, the adsorption media at the top of the adsorption zones becomes saturated and the adsorption zones begin to simultaneously migrate downward through the vessels until fluoride starts to break through. Breakthrough is defined as the first detectable amount of fluoride appearing in the effluent of a vessel.

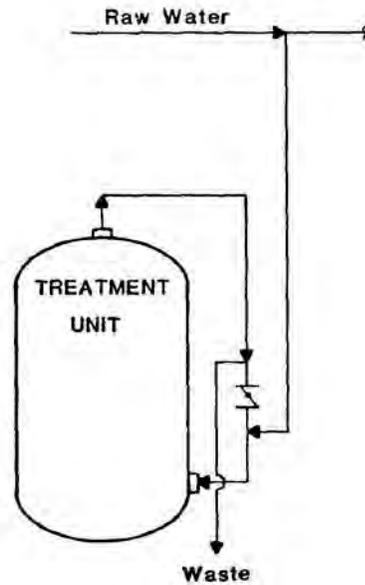
As treatment progresses, the adsorption zones in both vessels continue to move downward through the vessels until fluoride concentrations in the vessel effluent have reached a set breakthrough level (e.g., 80% of MCL). Both vessels are then taken offline for regeneration. To minimize system downtime, regeneration can be staggered with a vessel in the regeneration mode while the other continues to be in the service mode. Until both vessels have been regenerated, the system resumes to be in the normal service mode.

In the vessel that has completed the regeneration process, the treated water pH gradually drops to the adjusted raw water pH level where it remains through the duration of the run. Because the pH of the treated water is lower than the normally accepted minimum pH of 6.5, it should be raised either by chemical addition, aeration, and/or blending with raw water. Regardless of the method of pH adjustment, it should take place and be stabilized at the desired level prior to delivering the treated water into the distribution system.

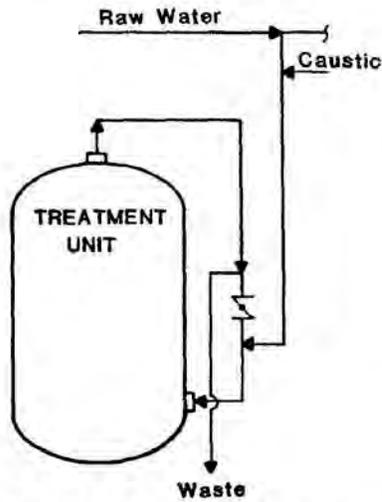
High pH in the treated water is also a concern. Normally the maximum allowable pH is 8.5; however, there are exceptions where pH 9.0 may be permitted. If desired, the treated water can flow past a failsafe pH sensor with high and low level alarms. If there is a pH excursion exceeding the allowable limits, an interlock (incorporating the pH alarms with the well pump(s) magnetic starter) de-energizes the well pump(s). Simultaneously, the chemical pumps shut down as their controls are interlocked with the well pump(s) power circuitry. The failsafe pH override automatically prevents any treated water for which pH is out of tolerance from entering the distribution system. In the event of such an excursion, the operator manually controls the well pump(s) to divert the unacceptable water to waste, determine the cause of the deviation, and make corrections prior to placing the treatment system back on line. Probable causes for treated water pH deviations are: changes in water flowrate, acid flowrate, caustic flowrate, and raw water chemistry.



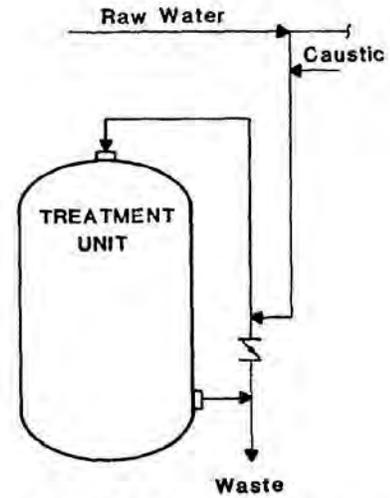
TREATMENT AND DOWNFLOW RINSE



BACKWASH AND UPFLOW RINSE



UPFLOW REGENERATION



DOWNFLOW REGENERATION

NOTE: For Clarity Only Relevant Pipes And Shutoff Valves Are Shown.

Figure 4-2. Example Operating Mode Flow Schematics

A treatment run can be extended by blending treated water in which the fluoride level exceeds the MCL with treated water with a low fluoride level. This can be done either in the effluent main leaving the treatment plant, in the storage reservoir or bypassing raw water to blend with treated water. During a treatment run, there is a period when the fluoride level of the treated water is well below one half of the MCL. As breakthrough occurs, there is a period of slowly increasing fluoride concentration in the treated water. Blending in the effluent main entails staggering the treatment cycles of two or more treatment units. This can be accomplished by continuing treatment in one unit after its increasing fluoride level has surpassed the MCL and blending it with low fluoride effluent from one or more units that is in the early stage of a treatment cycle. The operator can extend the run until the fluoride level reaches at least twice the MCL before terminating the run. As the fluoride level gets higher the operator must reduce the flowrate to maintain the combined high and low fluoride levels at an acceptable average. The same processes take place in the storage reservoir using one or more treatment units.

These blending practices can significantly increase the fluoride loading on the alumina and result in lower operating costs. As noted by in the original fluoride design manual (Rubel, 1984), the increase in fluoride loading can achieve 25 to 50% or even 100%. It should be noted that the higher the raw water fluoride level, the greater the adsorption capacity. Since there are many other factors that can affect this capacity, the precise amount is difficult to predict. The operator must be cognizant of the fact that the more water treated during a run, the lower the operating costs.

In raw waters where the fluoride level does not exceed two times the MCL, part of the raw water can bypass treatment and be blended back with the treated water. Water with even higher fluoride levels can also profit from bypassing, but the economic benefits rapidly diminish.

The operator can also reduce chemical consumption by blending high pH with low pH treated waters. This is accomplished during the period when one treatment unit has recently been regenerated and treated water pH is still high. A skilled operator develops many techniques such as this to minimize operating costs.

High iron and manganese contents in raw water can cause problems to the AA treatment process. Iron oxidizes, precipitates, and is filtered from water by AA. This results in increased pressure drop and shortened treatment runs. Raw water iron content greater than 0.3 mg/L is a cause for concern. However, if the iron concentration is above 0.3 mg/L, the secondary MCL, an iron removal process should be considered as the treatment process for fluoride removal in place of the adsorptive media process because of the capability of the process to remove fluoride.

4.3.2 Backwash Mode. It is important that the bed be backwashed with raw water after each treatment run prior to regeneration for two reasons. First, any suspended solids that have been filtered by the bed tend to blind the bed. Therefore, these particles should be removed from the bed. Second, even though filtration may have been negligible, the downward flow tends to pack the bed. An upflow backwash will expand the bed, and break up any tendency towards wall effects and channeling. A backwash rate of 7 gpm/ft² will expand the 28 × 48 mesh AA bed approximately 50%. The operator needs to carefully watch bed expansion and adjust backwash rate to avoid backwashing granular bed material out of the vessel. Normally backwashing lasts 10 min or until all suspended solids are removed from the media. Readers are referred to Table 4-1 for valve positions for the backwash mode. The basic flow schematic for the backwash mode of a lead-lag system is shown in Figure 4-2.

For most effective backwash, it is recommended that the vessel be drained prior to backwash. As backwash water flows into a drained bed, it lifts the entire bed approximately 1 ft prior to the bed fluidizing. This action provides an efficient scouring action without excessive abrasion to the adsorptive media grains. Backwash wastewater samples should be monitored to determine that suspended solids are

being removed and AA media is not being washed out of the bed. Excessive backwash causes abrasion that wears down activated alumina grains, and also wastes raw water and increases the wastewater disposal volume. Therefore, backwash volume should be minimized.

It is prudent to periodically inspect the media level of each treatment bed to determine whether bed volume has changed. If desired, the treatment vessels can be replenished with virgin AA and backwashed prior to being returned to the service mode.

4.3.3 Regeneration Mode. Upon completion of a treatment run, the AA beds can be regenerated using a two-step (upflow and then downflow) or a one-step (upflow or downflow) regeneration process. The two-step process involves an upflow regeneration step following draining of the bed after the backwash mode. The upflow regeneration is followed by an upflow rinse. The vessel is then drained to the top of the treatment bed prior to a downflow regeneration step. The one-step process utilizes only upflow or downflow regeneration to complete the process. Both processes use a 1% (by weight) NaOH solution.

The objective of regeneration is to remove as much fluoride ions (and other co-contaminants) as possible from the media before returning the bed to the treatment mode. Fluoride ions lose their attraction (adsorptive force) and become repelled by the alumina when the pH rises above 10.5. The higher the pH, the faster and more efficient the regeneration. However, too high a pH not only costs more (because of higher caustic consumption for media regeneration and higher acid consumption for media neutralization), but is also increasingly more aggressive to the AA material and causes the media to dissolve. The 1% NaOH solution (at pH 13.0) is sufficient to remove most fluoride ions while keeping the media dissolution to the minimum. When other co-contaminants such as arsenic also exist, the caustic concentration must be increased to as high as 4% to effectively remove arsenic (and fluoride) from the media. As described in Section 3.0, the dilution of the caustic takes place at an injector in the regeneration water piping. Both the raw water and the 50% NaOH are metered prior to injection into the regeneration main. The accuracy of the metering ranges from $\pm 2\%$ to $\pm 5\%$ depending on the type of flow instrumentation.

The rule of thumb for the volume of 1% caustic solution required per AA regeneration step is 30 gal/ft³ of treatment media. For the two-step process, the actual regeneration time exclusive of draining, flushing and neutralization is 100 min, i.e., 50 min per step for the solution to flow through the bed. For a 5-ft-deep treatment bed, a flow of 3.0 gpm/ft² for a period of 50 min for each regeneration step is sufficient. This equates to approximately 0.4 gal 50% NaOH per cubic foot of media for each regeneration step (upflow and downflow). Table 4-1 shows the valve positions during the two-step regeneration process. The basic flow schematics for the regeneration modes are illustrated in Figure 4-2. Plant A in Appendix C follows a regeneration regime modified from this two-step process.

After backwash and prior to caustic regeneration, the bed should be drained to remove water, which dilutes the caustic concentration. Upon completion of the 50-min upflow regeneration, the caustic feed pump is turned off and the caustic soda day tank refilled. The raw water continues to flow for 60 min at 2.5 gpm/ft² flowrate upward through the bed, flushing out the fluoride. After this rinse step is completed, the vessel is drained to the top of the treatment bed, again to remove dilution water. The downflow regeneration then takes place for 50 min. The downflow regeneration is followed by draining fluid down to the top of the bed prior to the start of the acid neutralization step.

For the one-step upflow regeneration process, the bed is backwashed and drained prior to applying caustic upflow similar to the first part of the two-step regeneration process. The upflow regeneration is followed by draining fluid down to the top of the bed prior to the start of the neutralization step. For the one-step downflow regeneration process, the bed is backwashed and drained to the top of the bed prior to the

commencement of downflow regeneration. The downflow regeneration is then followed by draining to the top of the bed prior to the start of acid neutralization.

The one-step regeneration process appears to be as effective as its two-step counterpart. As shown in Appendix C, Plants B utilizes a one-step downflow regeneration process, which draws 38.6 gal/ft³ of 1% caustic through the 420-ft³ bed at 270 gpm (or 2.4 gpm/ft²) for 60 min. This gives an EBCT of 11.6 min through the 3.7-ft-deep AA bed (versus 12.5 min through the 5-ft-deep bed described above). This one-step process with a shorter regeneration time (60 vs. 100 min) is also sufficient to completely regenerate the bed for sustainable system operation, according to the plant operator.

4.3.4 Neutralization Mode. Following caustic regeneration, the bed must be treated with acid prior to returning it to the treatment mode as rapidly as possible. The pH of the AA media after regeneration is about 13, which must be adjusted down to pH 5.5 for effective fluoride removal during the following treatment run. The minimum pH that can be safely exposed to the granular AA is 2.5. A pH lower than that can dissolve media and cause cementing of the bed (especially if the acidic water is allowed to stand in the bed for any period of time).

At the start of the downflow neutralization mode, the valves are positioned according to Table 4-1, and the flowrate is adjusted to that of the normal treatment mode. The basic flow schematic for the neutralization mode is illustrated in Figure 4-2. After the acid pump is started, the pH of the raw water is adjusted to 2.5. The acid feedrate again varies with the alkalinity of the raw water. The raw water flowrate may have to be reduced to achieve pH 2.5 at the maximum acid pump feedrate.

As the neutralization step proceeds, the pH of the bed effluent gradually drops below 13. The rate of pH reduction increases at an increasing rate. As the effluent pH drops below 10, the effluent fluoride level begins to drop below that of the raw water. At the point where the fluoride level drops below the MCL, the water becomes usable and can be directed to storage. When the effluent pH drops to 8.0, the raw water pH is adjusted up to 4.0 as the bed rapidly neutralizes. When the effluent pH drops to 6.5, the raw water pH is adjusted up to 5.5 where it remains through the duration of the treatment cycle. The regenerated bed now starts the next cycle in the treatment mode.

Prior to placement of the regenerated treatment unit into service, the operator should open the manway in the top head of the vessel to check the level of the treatment media. The operator may replace the lost AA by adding a proper amount to bring the bed back to the original level.

The operator should then backwash the bed with water adjusted to pH 5.5 for 30 min. The regenerated treatment unit will then be placed into service. An example of the two-step regeneration process is shown in Table 4-3.

The volume of wastewater produced during the regeneration of a treatment bed varies with the physical/chemical characteristics of the raw water. A rule of thumb that can assist the operator in his logistical handling is that 300-400 gal of wastewater is produced per cubic foot of AA during each regeneration. Typical volumes of wastewater generated per cubic foot of AA during each regeneration step for a hypothetical treatment bed are shown in Table 4-3. Operational experience at a specific treatment plant will present deviations from these quantities.

4.4 Operator Requirements

A qualified operator for a fluoride removal plant should have thorough fluoride removal process training, preferably at an existing treatment plant. The operator should be able to service pumps, piping systems,

instrumentation, and electrical accessories. The operator should be fully informed about the safety requirements and physical/chemical characteristics of both acid and caustic in all concentrations.

Table 4-3. Example Two-Step Process Conditions for Regeneration of an Activated Alumina Treatment System^(a)

Step No.	Step	Process Solution	Flow Direction	Flowrate (gpm/ft ²)	Time (min)	Wastewater (gal/ ft ³)
1	Backwash	Raw water	Upflow	7	10	60
2	Regeneration	1% NaOH	Upflow	1.2	50	15
3	Rinse	Raw water	Upflow	2.5	60	30
4	Regeneration	1% NaOH	Downflow	1.2	50	15
5	Neutralization	Raw Water adjusted to pH 2.5	Downflow	Varies	Time to achieve pH of 8.0	180
6	Neutralization	Raw water adjusted to pH 4.0	Downflow	Varies	Time to achieve pH of 6.5	
7	Neutralization	Raw water adjusted to pH 5.5	Downflow	Varies	Time to achieve pH of 5.5	
TOTAL						300

(a) Consult media or system suppliers for specific media regeneration/neutralization steps.

Corrosive chemical safety requirements as to clothing, equipment, antidotes, and procedures must be thoroughly understood. The operator should be thoroughly trained to run routine water analyses including the method for determining fluoride levels. The operator should be well grounded in mathematics for operation cost accounting and treatment run recordkeeping. The operator, above all, should be dependable and conscientious.

4.5 Laboratory Requirements

In addition to the O&M manual, the treatment plant should have the latest edition of *Standard Methods for the Examination of Water and Wastewater* prepared jointly by the American Public Health Association–American Water Works Association–Water Environment Federation (1995). This manual supplies the plant operator with necessary information for acceptable methods for analyzing water. A recommended list of items for analysis is illustrated in Table 3-1. The primary requirement is accurate analysis for fluoride and determination of pH. As long as pH meters are calibrated and cleaned regularly, high precision measurements are easily obtained. Care should be exercised to prevent contamination of pH buffers.

Fluoride can be effectively preserved in field samples and analyzed by several analytical methods down to the MCL of 4 mg/L or less. Preservation of fluoride is accomplished by acidifying the sample to pH <2. Fluoride may be analyzed using several EPA approved analytical methods: ion chromatography (IC), selective fluoride electrode, etc.

4.6 Operating Records

A system of records should be maintained on file at the treatment plant covering plant activity, plant procedures, raw water chemical analyses, plant expenditures, and inventory of materials (spare parts, tools, etc.). The plant operator should have the responsibility of managing all aspects of the treatment

plant operation. The operator is accountable to the water system management. The recommended record system should include, but not be limited to, the items described in the following subsections.

4.6.1 Plant Log. A daily log should be maintained in which the plant operator records daily activities at the plant. This record should include a listing of scheduled maintenance, unscheduled maintenance, plant visitors, purchases, abnormal weather conditions, injuries, sampling for state and other regulatory agencies, etc. This record should also be used as a tool for planning future routine and special activities.

4.6.2 Operation Log. The operator should maintain a log sheet for each treatment run for each treatment unit. Thereby, a permanent plant performance record will be on file. Figure 4-3 illustrates a copy of a suggested condensed form.

4.6.3 Water Analysis Reports. It is recommended that the plant operator run an analysis of raw and treated fluoride levels once each week for each unit, and should run a total raw water analysis once per month. Changes in raw water may necessitate changes in the treatment process. Raw water changes that can impact the treatment process include, but are not limited to, pH, alkalinity, iron, manganese, hardness, phosphate, silica, sulfate, sodium, TDS, and turbidity. Table 3-1 illustrates a copy of a suggested form. A permanent file of these reports can be a valuable tool.

4.6.4 Plant Operating Cost Records. Using accounting forms supplied by the water system's accountants, the plant operator should keep a complete record of purchases of all spare parts, chemicals, laboratory equipment and reagents, tools, services, and other sundry items. This should be supplemented by a file of up-to-date competitive prices for items that have been previously purchased.

4.6.5 Correspondence Files. The plant operator should retain copies of all correspondence pertaining to the treatment plant in chronological order. Included would be intradepartmental notes and memos, in addition to correspondence with other individuals and/or organizations.

4.6.6 Regulatory Agency Reports. The plant operator should maintain a complete file of copies of all reports received from state, county, or other regulatory agencies pertaining to the treatment plant.

4.6.7 Miscellaneous Forms. The operator should have an adequate supply of accident and insurance forms.

4.7 Treatment Plant Maintenance

The maintenance concept for the fluoride removal water treatment plant is to isolate the equipment to be serviced by means of shutoff valves, vent and drain lines (as required), repair or replace equipment, fill lines, open valves, and start service. To accomplish this, all equipment items are equipped with isolating valves, and all piping systems have vents at high points and drains at low points.

Equipment manufacturers' recommended spare parts should be stocked at the treatment plant to avoid lengthy maintenance shutdowns.

If the entire treatment plant needs to be shut down and the plant has bypass and if the bypass piping is large enough to handle the full flow, the plant itself can be bypassed. This can be done by closing the butterfly valves in the raw water and treated water line and then opening the butterfly valve in the bypass line. This would result in untreated water with excessively high fluoride being pumped to distribution, an event that should not occur without the approval of the water system manager and the regulatory agency.

4.8 Equipment Maintenance

Equipment manufacturer's maintenance instructions should be included in the Suppliers Equipment Instructions section of the O&M Manual.

4.9 Treatment Media Maintenance

The plant operator should inspect the surface of each treatment bed at least once a month. If the level of a bed lowers more than 8 in., makeup adsorptive media should be added. Makeup adsorptive media should be evenly distributed. There should be a minimum depth of 2.0 ft of water above the surface of the existing bed through which the makeup adsorptive media will be added. The vessel should be closed immediately and backwashed at 7 gpm/ft² (or at rate recommended by the manufacturer) for at least 30 min. It is very important to flush the fines out of the virgin activated alumina as soon as it is wetted.

It is important that the treatment beds should not remain in the drained condition for more than one hour. Treatment units not in use should remain flooded.

4.10 Treatment Chemicals Supply

The operator should carefully monitor the consumption of liquid chemicals and reorder when necessary. The operator should have a method of determining the depth of liquid in the storage tank (e.g., dipstick) and equating that to the volume of liquid in the tank. Figure 4-4 illustrates a liquid depth versus volume curve for a 5,000-gal horizontal cylindrical tank with dished head.

4.11 Housekeeping

The plant operator should wash down all equipment at least once per month. Floors should be swept. Bathroom and laboratory fixtures should be cleaned once per week. All light bulbs should be replaced immediately upon failure. Emergency shower and eyewash should be tested once per week. Any chemical spill should be neutralized and cleaned up immediately. Equipment should be repainted at least once every five years.

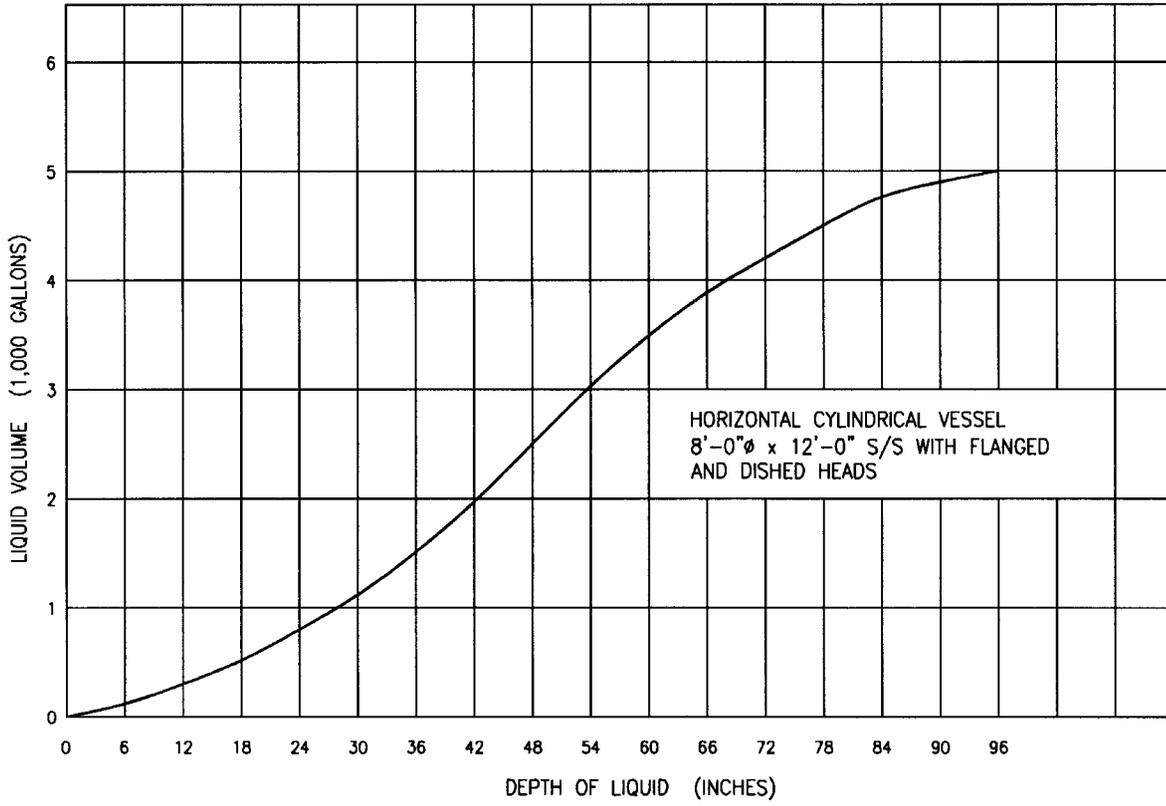


Figure 4-4. 5,000-gal Chemical Storage Tank – Liquid Volume

5.0: CENTRAL TREATMENT PLANT CAPITAL AND OPERATING COSTS

5.1 Introduction

The primary objective of the central treatment plant design is to provide the client with a least expensive AA system that can remove excess fluoride and meet the peak water demand year round. The system not only should work efficiently and reliably but also be simple and inexpensive to operate. Therefore, the economic feasibility evaluation should include initial capital and O&M costs.

In addition to the system flowrate, many other factors can impact capital costs. These include, but are not limited to, the following:

- (1) Raw water quality, including but not limited to pH, fluoride concentration; presence of competing anions such as arsenic, silica and phosphate; and amounts of alkalinity, total organic carbon (TOC), hardness, iron and manganese
- (2) Chemical supply logistics
- (3) Manual vs. automatic operation
- (4) Backwash and regeneration wastewater disposal requirements
- (5) Ambient conditions including climate (temperature, precipitation, wind, etc.), soil condition, seismic zone, and 100-year flood plain
- (6) Existing and planned (future) potable water system parameters
 - (i) Number and location of wells
 - (ii) Water storage (amount, elevation, and location)
 - (iii) Distribution (location, peak flows, total flow, pressure, etc.)
 - (iv) Consumption (daily and annual)
- (7) Financial considerations (cost trends, capital financing costs, cash flow, labor rates, utility rates, chemical costs, etc.).

Operating costs are normally passed directly on water customers in their monthly water bills. These costs include the following:

- (1) Treatment chemical costs
- (2) Operating labor costs
- (3) Utility costs
- (4) Replacement media costs
- (5) Replacement parts and miscellaneous materials costs

As the consumer's water bill normally is based on metered water consumption, the costs for treatment are prorated on the unit of volume measurement, which is usually 1,000 gal (i.e., ¢/1,000 gal). Some systems do not meter consumption; instead, they charge a flat monthly rate based upon the size of the branch connection to the water main. Although this latter mode of distribution saves the cost of meters as well as the reading of meters, it does not promote water conservation. Therefore, far more water is pumped, treated, and distributed, resulting in a net increase in operating cost.

The common denominator that applies to both the operating cost and the bill for water consumption is the unit of volume, 1,000 gal. Each operating cost factor can be reduced to cost/1,000 gal. The sum total of the annual operating costs based on total water production yields the cost per 1,000 gal.

5.2 Capital Costs

5.2.1 Discussion of Cost Variables. All cost variables mentioned above have direct impact on the costs of a central treatment system. Ideally, conditions exist in which a minimum cost system can be designed and fabricated. A hypothetical example of an ideal situation would resemble the following:

- (1) Raw water quality presents few or no challenges to AA, i.e., with moderate temperature and contains low alkalinity, low concentrations of competitive ions, etc.
- (2) Acid and caustic stored in large quantities onsite for other purposes
- (3) Manual operation by labor that is normally at the site with sufficient spare time
- (4) Existing wastewater disposal capability adjacent to treatment site (e.g., a large tailings pond at an open pit mine)
- (5) Warm moderate climate with minimal precipitation and no freezing, no high temperature, and no high wind; existing concrete pad located on well compacted, high-bearing capacity soil; no seismic requirements.
- (6) Single well pumping to subsurface storage reservoir with capacity for peak consumption day
- (7) Funding, space, etc., available.

This ideal situation never exists in reality. Occasionally one or more of the ideal conditions occur, but the frequency is low. If the final estimate for the example used in Appendix B is revised to incorporate the above ideal conditions, the cost estimate would be reduced about 60% (Rubel, 1984). Conversely, adverse conditions could accumulate, resulting in a cost far in excess of that for the typical treatment system for the same treatment capability. The following subsections provide the basic insight needed to benefit from the above variables.

5.2.1.1 Water Chemistry. The water chemistry can affect capital as well as operating costs. With a clear picture of the raw water quality, its possible variations and its adverse characteristics, the effect on the capital cost can be determined readily. Higher water temperature (greater than 100°F) requires higher cost piping material and/or pipe support. Varying water temperature requires inclusion of special provisions for thermal expansion and contraction. Very high fluoride may require larger media vessels to reduce regeneration frequency. Higher alkalinity requires higher acid consumption for pH adjustment resulting in the needs for larger feed pumps, day tank, piping, etc. This may result in an aeration step for post treatment pH adjustment in place of caustic addition. High turbidity, iron, manganese, suspended solids, and/or other contaminants can require the addition of pretreatment steps to accomplish removal prior to fluoride removal, or the implementation of a different fluoride removal treatment method.

Each of the physical and chemical characteristics of the raw water should be evaluated. The technical as well as the economical feasibility for the entire project could hinge on these factors.

5.2.1.2 Chemical Supply Logistics. Sulfuric acid (normally 66°B' H₂SO₄) and caustic soda (normally 50% NaOH) are commercially available and are usually the least expensive chemicals to use for pH adjustment. Other chemicals such as hydrochloric acid and caustic potash (KOH) are technically acceptable, but almost always more costly, and therefore are not commonly used. The acid and caustic are much cheaper when purchased in bulk quantities, usually 48,000-lb tank trucks. In very small plants, the cost of storage tanks for those volumes is not justified and therefore, drums and carboys with smaller volumes but higher unit prices are procured. In very large treatment plants, cost can be lowered by procuring the chemicals via 200,000-lb railroad tank cars. However, this approach requires a rail siding and rail unloading facility; nevertheless, it does present an option of lowering the overall cost.

A chemical unloading rail terminal presents another intriguing option for facilities with multiple treatment plants. In this approach, smaller site storage tanks are supplied via “mini tank trucks” relaying chemicals to the treatment site from the rail terminal. This brings down the size (and cost) of chemical storage tanks at each site. However, this could increase the truck traffic of corrosive chemicals through populated areas, a risk that may not be acceptable.

5.2.1.3 Manual Versus Automatic Operation. Automatic operation is technically feasible. However, the periodic presence of an operator is always required. The capital costs of automation for computer hard-ware/software, valve operators, controls, instrumentation, etc., as well as maintenance costs may exceed budget limits that the client will accept. Therefore, either manual or semiautomatic operation is normally furnished. The advantages and disadvantages of manual, automatic and semiautomatic operation require careful evaluation prior to determination of the proper selection.

5.2.1.4 Backwash and Regeneration Disposal Concept. Regeneration wastewater and waste solids processing and disposal is not included in the scope of this document. Depending on wastewater discharge limits established by the U.S. EPA, state and local regulatory authorities, wastewater disposal can be a significant cost item in the capital (and operating) cost projection. Requirements can vary from zero discharge to discharge into an available existing receiving facility. Disposal and/or discharge can be accomplished by chemical precipitation of calcium fluoride or aluminum hydroxide with subsequent dewatering of precipitated solids and adjustment of pH. The dewatered solids should pass the U.S. EPA Toxicity Characteristic Leaching Procedure (TCLP) test and/or California Waste Extraction Test (WET) test (if in the state of California). The wastewater, though containing low levels of fluoride, will contain elevated levels of TDS, sodium, and sulfate. If regulatory agency permits disposal by conventional methods such as surface discharge, percolation, and evaporation pond, the disposal costs are not large. The total volume of wastewater regeneration generally is 300 to 400 gal/ft³ of AA media.

In the event a zero discharge of wastewater is required, the wastewater supernatant and filtrate (from solids dewatering) should be fed back to the head of the treatment plant and very slowly added to the raw water. This concept, however, has not been incorporated in a full-scale treatment plant.

5.2.1.5 Ambient Conditions

Climate: Temperature extremes, precipitation, and high wind will necessitate a building to house the treatment system equipment. High temperature along with direct sunlight adversely affects the strength of plastic piping materials. Freezing is obviously damaging to piping and in some extreme cases also to tanks. Temperature variation introduces requirements for special thermal expansion/contraction provisions. A building with heating and/or cooling and adequate insulation will eliminate these problems and their costs, but will introduce the cost of the building. The building cost should reflect wind loads as well as thermal and seismic requirements. Operator comfort in place of economic considerations may dictate building costs.

The installation costs for the buildings and regeneration wastewater surge tank along with their associated civil work becomes a major portion of the overall capital cost. Care in interpreting the climatological conditions and their requirements are necessary.

Soil Conditions: Unless soil-boring data are already available for the treatment system site, at least one boring in the location of the foundation for each heavy equipment item (treatment vessels, chemical storage tanks, and regeneration wastewater surge tank) is required. If the quality of the soil is questionable (fill, or very poor load-bearing capacity), additional soil borings should be obtained. Poor soil may require costly excavation/backfill and foundations.

Combinations of poor soil with rock or large boulders can make foundation work more complex and costly. Rock and boulders in combination with extreme temperatures can result in very high installation costs for subsurface raw, treated, and wastewater pipe mains.

Seismic Zone: Compliance with the seismic design requirements of the local building codes can impact capital costs. Buildings and tall slender equipment are vulnerable to seismic loads. The magnitude of seismic design requirements should be determined. In zones of extreme seismic activity, low profile equipment and buildings are recommended.

100-Year Flood Plan: For water treatment facilities located within a 100-year flood plain, the entire site should be relocated to another site outside of the 100-year flood plain, be elevated 3 ft above the 100-year flood plain level, or be protected on all sides by an armored berm that extends a minimum of 3 ft above the 100-year flood plain level.

5.2.1.6 Existing and Planned (Future) Water System Parameters. Many existing and planned (future) facility configurations can either significantly increase or decrease the capital cost. The most important factors are discussed in this section.

Number and Location of Wells: When only one well requires treatment, the removal of fluoride should be accomplished prior to entering the distribution system. Theoretically, treatment can occur before or after entering storage. Practically speaking, treatment prior to entering storage is much easier to control because the treatment plant flowrate remains the same as the pump flowrate or will be constant. If treatment takes place after storage, or if there is no storage, flowrate is intermittent and variable, and pH control is only achievable for a sophisticated automatic pH control/acid feed system.

When more than one well requires treatment, a decision is required regarding whether a single treatment plant treating water from all wells manifolded together or individual treatment plants at each well present would be a more efficient and cost-effective concept. Factors such as distance between wells, distribution arrangement, system pressure, and variation in water quality should be evaluated in that decision. If all of the wells are in close proximity and pump similar quantity and quality of water, a single treatment plant serving the entire system is preferable. When wells are widely dispersed, manifolding costs become prohibitively expensive, thus dictating implementation of individual treatment plants at each well. Frequently, the distances may be such that the decision is not clear cut; then other variables such as water quality, system pressure, distribution configuration, land availability should be evaluated.

Systems that require multiple treatment plant installations can achieve cost savings by employing an identical or similar system at each location. This results in an assembly line approach to procurement, manufacture, assembly, installation, and operation. Material cost savings, labor reduction and engineering for a single configuration will reduce the cost for the individual plant.

Potable Water Storage Facilities: Similar to the wells, the number, size, and location of storage tanks can affect treatment plant size (flowrate) and capital costs. If there is no storage capacity in the system, the well pump should be capable of delivering a flowrate equal to the system momentary peak consumption; this can be many times the average flowrate for a peak day. Therefore, if no storage capacity exists, a storage tank should be added with the treatment system for treated water storage. Otherwise, automatic pH instruments and controls will be required to pace pH adjustment chemical feedrates to the varying process water flowrate.

Most systems have existing storage capacity. The storage may be underground reservoirs, ground level storage tanks, or elevated storage tanks (located on high ground or structurally supported standpipes). The first two require repressurization; the latter does not. The elevated storage tanks apply a

backpressure on the ground level treatment system requiring higher pressure (more costly) construction of treatment vessels and piping systems. If aeration of treated effluent for pH adjustment is selected with an elevated storage tank, the treated water should be contained in a clearwell and repumped to storage. However, the treatment system vessels and piping may be low-pressure construction. When storage is at or below ground level storage, loss of system pressure is not a factor.

The amount of storage capacity also affects treatment system cost. The larger the storage capacity (within limits), the lower the required treatment plant flowrate (and resulting cost). A minimum storage capacity of one-half of system peak day consumption is recommended.

Distribution and Consumption: The factors that determine the sizing of the treatment system are the well (or feed) pump flowrate, EBCT, storage capacity, and system consumption characteristics. Those features should be coordinated to provide a capacity to deliver a peak treated water supply to satisfy all possible conditions of peak consumption. If there is adequate storage capacity, the momentary peaks are dampened out. The peak day then defines the system capacity. The well (or feed) pump then is sized to deliver the peak daily requirement. The treatment system in turn is sized to treat a minimum of what the well (or feed) pump delivers.

The distribution system may anticipate future growth or increased consumption. The well (or feed) pump then should either pump a flow equal to or greater than the maximum anticipated peak daily flows, or be able to adjust to future increased flowrate. The treatment plant in turn should incorporate capacity to treat the ultimate peak flowrate or include provisions to increase the treatment capacity in the future.

5.2.1.7 Financial Considerations. Many financial factors should be considered by the designer and the client. The client can superimpose financial restrictions (beyond any of the technical factors mentioned above) which result in increased (or decreased) capital cost. These include, but are not limited to, the following: inflationary trends, interest rates, financing costs, land costs (or availability), cash flow, labor rates, electric utility rates, and chemical costs. All or some of these factors could affect the capital investment with reduced operating cost because interest rates are low, inflation is anticipated, cash is available, and labor and electric utility rates are high; or the opposite can be true. The varying combinations of factors that could develop are numerous; each one will affect the ultimate capital cost.

5.2.2 Capital Costs of Central Fluoride Removal Plants Based on Flowrate. Capital costs of central AA plants can be broken down into several categories such as process equipment (including treatment vessels, AA media, process piping/valves, instrument/controls, chemical storage tanks/containments, chemical pumps/piping, etc.), process equipment installation (including mechanical, electrical, painting, etc.), facility infrastructures (including treatment building/concrete, site work, wastewater pond, etc.), engineering fees and contingency. Capital investment costs can vary significantly especially with the inclusion of items such as facility infrastructures and various disposal options. For example, Plant B with a 900-gpm maximum flowrate invested \$900,000 for treatment vessels, media, face piping/valves (not including the bulk piping which was done by a separate contractor), instrumentation/controls, spent regenerate treatment (CaF₂ precipitation), and chemical storage/pumps/piping. Plant D also with a 900-gpm maximum flowrate invested over \$11,000,000 for everything stated above under Plant B plus the treatment building, a distribution pumping station, two storage tanks, and a sand separation device.

5.3 Operating Costs

5.3.1 Discussion of Cost Variables. Similar to capital costs, many variables affect operating costs. The following subsections discuss each of the operating costs previously listed.

5.3.1.1 Treatment Chemical Costs. The treatment chemicals discussed are limited to sulfuric acid (H_2SO_4) and caustic (NaOH). Both are highly corrosive, hazardous liquid chemicals that require compatible materials of construction, containment provisions, safety provisions, weather protection, and operator training. Although special precautions and training are required, they are routinely accomplished. Other acids and bases can be substituted for those chemicals, but they are usually more costly and therefore rarely considered. Other chemicals also are used for other requirements such as corrosion inhibition, precipitation of regeneration wastewater solids, dewatering of precipitated solids in wastewater, and disinfection; however, these are site-specific requirements that are not covered in this manual.

The chemicals used for treatment of water for public consumption require NSF/ANSI STD 60 certification by most state regulatory agencies. It is also recommended that chemical suppliers be required to certify that containers used to store and deliver the chemicals have not been used for any other chemical; or if they have, that they have been decontaminated according to procedures required by governing regulatory agencies.

Chemical costs are variable and have been volatile. Like all commodities, they are sensitive to the supply and demand fluctuation of the marketplace. The geographic location of a plant site in relation to that of a supplier has an impact on the delivered cost. In some cases, delivery costs are greater than chemical costs. The conceptual design evaluates the chemical logistics and determines the most cost-effective mode of procurement as well as whether chemicals for pH adjustment are economically feasible.

Chemical costs are sensitive to the volume and containment mode of the commodity purchased. Because commodity handling is minimized, bulk tank truck quantities entail the least cost. Tank truck quantities are normally 48,000 lb. Bulk deliveries require chemical storage tanks within containment basins located at the plant site with necessary safety provisions and weather protection. The same commodities can be routinely purchased in drums (55-gal or 30-gal), totes, carboys, gallon jugs, etc. These packaged quantities result in much higher unit prices than bulk quantities. Drum and other small container prices also depend on the quantities procured at one time. Small containers also introduce additional handling requirements for the treatment plant operator. For very small treatment systems, bulk procurement and storage is not justified unless the feedwater fluoride and alkalinity concentrations are extremely high. In special low flowrate systems where high fluoride and high alkalinity concentrations are present in the feedwater and drum quantity costs are significantly higher than bulk quantity costs, the increased chemical consumption could justify bulk purchase.

The chemistry of the raw water to be treated is the most significant factor affecting treatment chemical consumption and costs. Fluoride and alkalinity are the key ions in the raw water; the higher the concentration of either ion, the higher the chemical consumption and cost per 1,000 gal of treated water.

Acid Costs: The most cost-effective, commercially available chemical for lowering pH is concentrated sulfuric acid. Hydrochloric acid is also applicable, but it is more difficult to handle, increases chlorides (i.e., is corrosive), and usually is more costly. The chemical designation of commercially available sulfuric acid is 66°B' H_2SO_4 . Its concentration is 93.14%. The remaining 6.86% is water (plus other ions). The other ions that could be present should be evaluated and could result in a slight increase in their concentration in the treated water. Frequently, small quantities of iron and trace amounts of heavy metals are present. For water treatment service, there are stringent limits on the levels of contaminants in

the acid which will be rigidly enforced. NSF certification of the acid for use as an additive in drinking water is required.

The most economical method of procuring acid is in bulk tank truck quantities (48,000 lb), which are 3,100 gal each. The tank trucks are loaded at each acid manufacturer's site or at a distribution storage site and delivered directly to the treatment plant where the acid is transferred to the acid bulk storage tank. Transfer is accomplished by means of compressed air, which is provided by an air compressor on the truck (unless the treatment plant can provide the compressed air). In addition to the lower commodity price resulting from minimum handling and storage of the chemical, there is minimum chance of contamination. At large treatment plants where there is potential for high acid consumption, rail tank car quantity (200,000 lb) delivery, which is cheaper, may be justified. Capital expenditures for a 16,000-gal (minimum) storage tank and a rail spur with unloading equipment then are required.

The delivered costs of bulk tank truck quantities of sulfuric acid increased significantly during the last years. In 2003, the bulk delivery cost ranged from 4.5 to 6¢/lb (or \$90 to \$120/ton) depending on the geographic location of the treatment plant. (Drum quantity costs ranged from 10 to 12¢/lb or higher.) In 2013, the delivered cost to Plant A is 12.5¢/lb (or \$250/ton), more than twice a plant would pay in 2003.

The acid is consumed in three phases of the treatment process at every fluoride removal plant. First, it is used to adjust the raw water pH to the treatment requirement (5.5); second, it is used to rapidly neutralize the treatment bed immediately after regeneration; finally, it may be used for pH adjustment of the regeneration wastewater for discharge to sewer or other receiving facilities. This final application does not apply to treatment systems that discharge regeneration wastewater to lined evaporation ponds. The raw water alkalinity dictates the amount of acid required for the pH adjustment step. The AA fluoride removal process has been employed on natural waters with alkalinity values ranging from 10 to 1,500 mg/L (as CaCO₃) (Rubel, 1984).

The acid consumption for pH adjustment can be accurately projected by running a titration on a raw water sample. The cost of acid required for pH adjustment is then determined by extending the acid addition in mg/L to the weight (lb) required per 1,000 gal and multiplying by the commercial cost for the acid.

For the design example presented in Appendix B, a hypothetical feedwater analysis includes the following:

$$\begin{array}{l} \text{Total alkalinity (M)} = 220 \text{ mg/L (as CaCO}_3\text{)} \\ \text{pH} = 8.0. \end{array}$$

Based upon titration results, the quantity of 66°B' H₂SO₄ required to adjust the pH to 5.5 is 205 mg/L. The amount of acid required per 1,000 gal treated water is as follows:

$$\frac{205 \text{ mg}}{\text{L}} \times \frac{10^{-6} \text{ kg}}{\text{mg}} \times \frac{\text{lb}}{0.4545 \text{ kg}} \times 1000 \text{ gal} \times \frac{3.785 \text{ L}}{\text{gal}} = 1.71 \text{ lb/1,000 gal}$$

Therefore, for an acid bulk quantity price of 12.5¢/lb, the acid cost per 1,000 gal treated water is 21.25¢. If the acid is procured in drum quantities at 40¢/lb, the resulting cost is 67.5¢/1,000 gal. Conversely, if the feedwater total alkalinity had been 100 mg/L as CaCO₃ and the pH 7.5, then the resulting acid required to adjust pH to 5.5 would be 92.4 mg/L. That equates to 0.77 lb/1,000 gal, or 9.75¢/1,000 gal (for acid bulk quantity price of 12.5¢/lb). The acid requirement for pH adjustment in Appendix B is 9.69¢/1,000 gal.

The acid consumption for neutralization after regeneration is a function of the caustic concentration employed during regeneration and the raw water alkalinity. This quantity varies from plant to plant. The consumption also is a function of the raw water fluoride level, which dictates the regeneration frequency, and the volume of water over which this cost is distributed. The higher the fluoride level, the fewer gallons treated per treatment cycle. When projecting chemical costs and volumes, a rule of thumb is 10,000 gal of treated water per cycle per ft³ of AA with 6 mg/L raw water fluoride (this decreases to 4,000 gal/ft³ at 20 mg/L fluoride and increases to 16,000 gal/ft³ at 3 mg/L fluoride) (Figure 5-1). The weight of acid required for neutralization after regeneration is normally in the range of 1 to 2 lb/ft³ of the AA media.

Using acid bulk quantity price of 12.5¢/lb, the acid costs for neutralization after regeneration will fall in the range of \$1.44 to 2.88¢/1,000 gal of treated water.

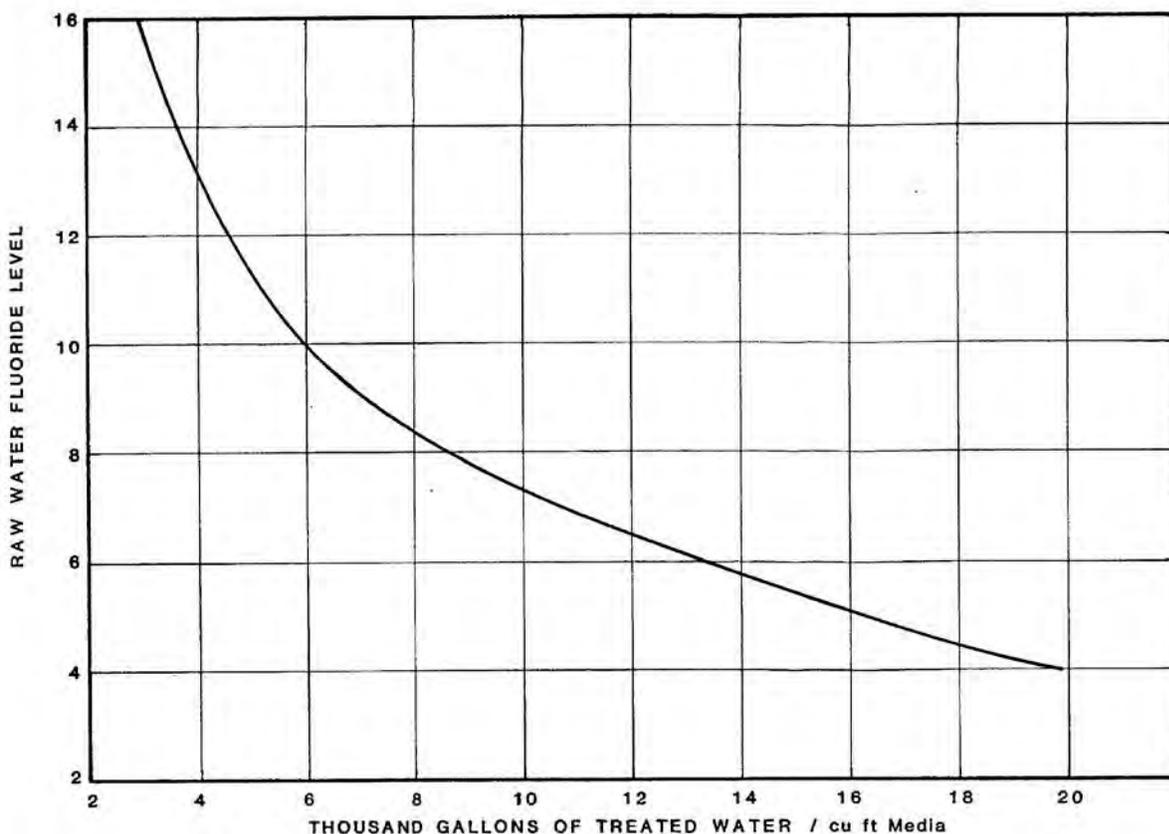


Figure 5-1. Curve Illustration Rule of Thumb for Volume of Water Treated per Cycle vs. Raw Water Fluoride Level

Caustic Costs: Caustic (NaOH) can be procured in either solid (100% NaOH) or liquid (50% NaOH or lower). The 50% NaOH is the standard concentration that is handled and applied to water treatment applications. That concentration is a byproduct of the chlorine manufacturing process. Therefore, it requires minimum handling to place it into a 48,000-lb bulk tank truck (3,850 gal). One challenge with 50% NaOH concentration is that it freezes at 55°F; it is also very viscous and difficult to transfer at temperatures below 70°F. Therefore, it normally requires heating. Also, because it is 50% water by weight, the freight is a cost factor. Solid caustic in bead or flake form is also readily available in drums or

bulk. Its freight cost is roughly half that of the liquid, but getting it into solution is difficult and dangerous. Regardless of the economics, solid caustic is not recommended for this application. Commercially available caustic in the 25% NaOH concentration has a freezing point of 0°F; however, freight costs for shipping this material are high (75% water). Capital costs for larger storage and pumping requirements are also increased. Even though heating and temperature protection are required, the 50% NaOH is recommended. Transferring caustic from tank trucks to storage tanks is accomplished with compressed air similar to the method for acid.

Similar to sulfuric acid, delivered costs of bulk tank truck quantities of 50% NaOH increased significantly in the last 10 years. In 2003, the bulk delivery costs ranged from 10 to 15¢/lb (or \$200 to \$300/ton) depending on the geographic location of the treatment plant. In 2013, Plant A paid 21¢/lb (\$420/ton) for the bulk delivery.

The caustic is consumed at two phases of the treatment process. First, it is used to raise the pH of the treated water to the level desired for distribution; second, it is used to raise the pH of the raw water to the level required for spent media regeneration. The first requirement may be reduced or replaced by aeration of the treated water to strip free CO₂ from the treated water.

The volume of 50% NaOH required for a 1% NaOH concentration regeneration (includes upflow and downflow requirements) is 0.4 gal (5 lb) per ft³ per regeneration cycle. As with the acid required for neutralization, the caustic consumption is a function of the raw water fluoride level, which dictates the regeneration frequency and the volume of water over which this cost is distributed. This varies from treatment system to treatment system.

The caustic consumption for treated water pH adjustment is also a function of raw water alkalinity and the desired treated water pH. The concentration of free CO₂ in the water after the initial pH adjustment with sulfuric acid will determine the caustic requirement. High CO₂ concentration or community objection to addition of sodium to the water supply could dictate the aeration method for pH adjustment. In general, when cost dictates the method, caustic pH adjustment is recommended when alkalinity is less than 100 mg/L and aeration is recommended when alkalinity is over 200 mg/L. In the alkalinity range of 100 to 200 mg/L, a general recommendation is difficult; other factors such as storage tank elevation must be considered. If caustic is used to raise the pH of the treated water, the quantity will be small. The consumption requirement can again be accurately determined by continuing the original titration required for acid to lower the pH to the treatment level of 5.5; then adding the 50% NaOH required to raise the pH to the desired level (e.g., 7.5). The cost of caustic required then is determined by extending the caustic addition in mg/L to the weight required per 1,000 gal and multiplying by the commercial price for the delivered caustic. The actual caustic cost will normally fall in the range of \$0.02 to \$0.12/1,000 gal of treated water.

For the design example presented in Appendix B for which the feedwater pH had been adjusted to 5.5 for treatment, the treated water pH is readjusted back to a desired level (e.g., pH 7.7). The 50% NaOH requirement determined by titration is 210 mg/L. The required quantity of 50% NaOH per 1,000 gal treated water is as follows:

$$(210 \text{ mg/L} \times 1,000 \text{ gal} \times 3.7854 \text{ L/gal}) / (1000 \text{ mg/g} \times 453.6 \text{ g/lb}) = 1.75 \text{ lb/1,000 gal}$$

Therefore, at a caustic bulk quantity price of 21¢/lb, the caustic cost per 1,000 gal is 36.8¢/1,000 gal. The caustic used in the estimated operating cost example in Appendix B is 36.6¢/1,000 gal.

Using the same activated alumina fluoride capacity (129,800 mg/ft³ [2,000 grains/ft³]) and volume of water treated per treatment cycle (2,700,000 gal/vessel) discussed in Section 4.a of Appendix B, the cost of caustic soda is as follows:

$$(0.4 \text{ gal/ft}^3/\text{regeneration cycle} \times 312 \text{ ft}^3/\text{vessel} \times 12.9 \text{ lb/gal of 50\% NaOH} \times 21\text{¢/lb}) / (2,700,000 \text{ gal/vessel/regeneration cycle}) = 12.5\text{¢/1,000 gal}$$

Therefore, for the example provided in Appendix B, caustic soda cost is 49.1¢/1,000 gal of water treated.

5.3.1.2 Operating Labor Costs. Operating labor costs are difficult to quantify. The operator is required to be dependable and competent; however, the position is not always full-time. Depending on the size of the system and the other duties available for the operator, the operator's time should be distributed over several accounting categories. Except for days when spent media regeneration takes place, the treatment plant normally requires less than 2 hr per day of operator attention. During regeneration, the operator may be required to spend approximately 8 hr over a 12-hr period.

On routine operating days, the operator checks the system to see that pH is being controlled, takes and analyzes water samples, checks instruments (flow, temperature, pressure), and makes entries in daily logs. The only exceptions to the normal routine include special activities such as media regeneration, equipment maintenance and chemical tank truck deliveries. During the remainder of the time, the operator is able to operate and maintain other systems (distribution, pumps, storage, etc.), read meters, or handle other municipal responsibilities (e.g., operate sewage treatment plant). There should always be a second operator available to take over in case of an emergency; that individual should be well versed in the operation of the plant.

Using the example treatment plant presented in Appendix B, the cost of operational labor will be as follows (it is assumed that the hours not used for treatment plant operation will be efficiently used on other duties):

Given:

Flowrate =	600 gpm	
Annual average utilization	=	40%
Number of regenerations per year	=	52
Number of hours daily	=	1.5 hr
Operator annual salary	=	\$35,000
Overhead and fringe benefits	=	30%
Available hours per year	=	2,000/man

Then:

Number of hours on regeneration/year	52×8	=	416 hr
Number of hours on routine operations/year	$1.5 \times (365 - 52)$	=	469.5 hr
Total plant operator time		=	885.5 hr

Operator hourly rate	$35,000 / 2,000$	=	\$17.50/hr
30% (overhead and fringe benefits)		=	<u>\$ 5.25/hr</u>
Operator Rate			\$22.75/hr

Total operator cost: $885.5 \text{ hr/year} \times \$22.75/\text{hr} = \$20,145/\text{year}$

Total gallons water produced:
 $0.4(600 \text{ gpm}) \times 1,440 \text{ min/day} \times 365 \text{ days/year} =$
126,144,000 gal/year

Labor cost/1,000 gal $\$20,145/126,144 (1,000 \text{ gal}) =$
\$0.16/1,000 gal.

If the operator had no other responsibilities and the operator's entire salary were expended against this treatment plant operation, the operating labor cost would become \$0.36/1,000 gal. Obviously, there are many variables, which can be controlled in different ways. Depending on the operational philosophy of the designer/planner/manager, the operating labor cost can be minimized or maximized over a very broad range. In the case of a very high production plant, the operating labor requirement is not significantly larger than that for a very small treatment plant. Therefore, depending on relative salaries, the resulting costs per 1,000 gal can range from a few cents to more than a dollar. In proper perspective, the operating labor cost should fall in the \$0.06 to \$0.20/ 1,000-gal range.

If the treatment plant in the example in Appendix B had used automatic operation in place of manual operation, the operating labor costs might be lower. However, because a higher skilled operator is required to maintain and calibrate the more sophisticated instrumentation and control equipment, the operating labor cost may not be lower. Therefore, no reduction of operating labor cost is assumed for systems with automatic operation.

5.3.1.3 Utility Costs. Utility costs are normally electricity bills. However, there can also be telephone and natural gas (or oil) utility costs. Telephone service to the treatment building is recommended as a safety precaution in case of accident as well as operator convenience. Costs for that service should be the minimum available monthly rate. Depending upon the local climate, the costs for heating can vary. The purpose of the building is to protect the equipment from elements (primarily freezing), not for operator comfort. Normally the treatment units act as heat sinks, maintaining an insulated building at a temperature near that of the raw water. In cold climates, the building should have an auxiliary heat source to prevent freezing of pipes in the event that the water is not flowing. If the client determines that the treatment building is to serve additional functions, heating to a comfort temperature could be an additional required cost.

Electric power is needed for the following functions:

- (1) Chemical pumps
- (2) pH controls
- (3) Caustic storage tank immersion heater
- (4) Lighting
- (5) Convenience receptacle
- (6) Aeration unit blower (optional)
- (7) Repressurization pump (optional)
- (8) Extra load on well pump for regeneration/backwash wastewater, and loss of head through the treatment system.

Items 1, 2, 4, and 5 are negligible. Item 3 is a function of the climate and the heat losses through the insulation. Provisions to conserve energy for this function should be incorporated. Item 6 is a relatively small load (1-3 hp blower motor). Item 7 is potentially the biggest electrical load. This requirement only

exists when aeration is used to adjust treated water pH, and the water is pumped to an elevated storage tank. This electrical load can be equal to the well pump motor load. However, when repressurization is a requirement, then the well pump should be modified to reduce its discharge pressure capability to only that which is required to pump the raw water through treatment into the clearwell in place of the pressure to pump to the elevated storage tank. Then the net increase of electrical energy consumption is nearly negated. Item 8 amounts to 3-5% of the well pump electrical energy consumption.

The electrical utility rates also vary considerably from one geographic location to another. According to the U.S. Energy Information Administration, industrial electricity rates in April 2013 varied from \$0.05 to \$0.26/kWh (http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a). Under normal operating conditions, the electrical utility costs can range from \$0.01 to \$0.10 per 1,000 gal of water treated.

5.3.1.4 Media Replacement Costs. The consumption of treatment media per regeneration for a system with process water pH adjustment and spent media regeneration in a well-operated AA removal water treatment plant is about 1% of the bed volume (Plant A reported a loss of 2.6% per regeneration cycle). The loss of media is caused by dissolution of a small amount of aluminum during the regeneration and neutralization steps where excessively high and/or low pH solutions are in contact with AA. If the pH of the regeneration solution exceeds 1.5% NaOH, the solution becomes increasingly aggressive to AA. Similarly, if the pH of the neutralization solution is lower than pH 2.0, a more drastic AA dissolution takes place.

There are additional ways in which the media can be lost. Backwash, if conducted carelessly, can result in media carry over. An excessive backwash rate can expand the AA bed by an amount that carries the media out of the vessel. Monitoring the backwash water will detect and provide prevention of that. If backwash water flows into the wastewater surge tank, the lost media can be recovered.

Another way to lose media is through the effluent underdrain (collection system) within the vessel. If media grains ever appear in the treated effluent, the treatment unit should be immediately taken out of service for inspection (and repair) of the collection system.

Media replacement costs are difficult to predict. Significant media replacement can occur at a treatment plant where backwash at an excessive rate for an extensive period has been required to remove filtered solids from the media. A plant in which suspended solids in the raw water require frequent extended backwashing is vulnerable to media loss problems. For systems encountering such conditions an upstream filter (e.g., bag filter) should be evaluated.

A typical pricing structure for a representative AA product in 2001 is provided in Table 5-1. In 2013, Plant A pays \$1.73/lb for 37,000 lb of media in 20 supersacks (each containing 1850 lb).

Table 5-1. 2001 Price for Typical –28, +48 Mesh Activated Alumina

Quantity	Price
2,000–10,000 lb	\$1.00/lb
12,000–20,000 lb	0.90/lb
22,000–38,000 lb	0.75/lb
40,000 lb and over	0.70/lb

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Appendix A

Summary of Subsystems Including Components

The items that are designated as “optional” are not mandatory requirements. Some of those items may already be included in systems other than treatment and therefore, would be redundant. Other items, though desirable, are not mandatory. Automatic and semiautomatic operation is optional. Therefore, for each instrument and control item, though not indicated for clarity, there is an automatic option.

1. Raw Water Influent Main
 - a. Flow Control
 - b. Flowrate measurement, flow total
 - c. Acid injection for pH adjustment
 - d. In-line static mixer
 - e. pH measurement, indicator, alarm, and fail-safe control
 - f. Pressure indicator
 - g. Pressure control (optional)
 - h. Backflow preventer
 - i. Sample before pH adjustment piped to sample panel (optional)
 - j. Sample after pH adjustment piped to sample panel (optional)
 - k. Isolation valve
 - l. Temperature indicator (optional)

2. Intervessel Pipe Manifold
 - a. Process control valves
 - b. Pressure indicators
 - c. Sample piped to sample panel (optional)

3. Treated Water Effluent Main
 - a. Caustic injection for pH adjustment
 - b. In-line static mixer
 - c. pH measurement, indicator, alarm and fail-safe control
 - d. Sample after pH adjustment piped to sample panel (optional)
 - e. Pressure indicator
 - f. Aeration subsystem(optional)
 - i. Air blower (optional)
 - ii. Clear well (optional)
 - g. Booster or repressurization pump (optional)
 - h. Disinfection injection (optional)
 - i. Isolation valve

4. Raw Water Bypass Main
 - a. Flow control
 - b. Flowrate measurement, flow total
 - c. Backflow preventer
 - d. Isolation valve

5. Backwash/Regeneration Feed Main
 - a. Flow control
 - b. Flowrate measurement, flow total
 - c. Caustic injection for pH adjustment
 - d. Acid injection for pH adjustment
 - e. In-line static mixer
 - f. pH measurement
 - g. Sample after pH adjustment piped to sample panel (optional)

- h. Backflow preventer
 - i. Isolation valve
6. Wastewater Main
- a. Backflow preventer
 - b. Process isolation valves
 - c. Acid injection for pH adjustment (optional)
 - d. Chemical injection (optional)
 - e. In-line static mixer (optional)
 - f. Sample after chemical injection piped to sample panel (optional)
7. Treatment Unit
- a. Pressure vessel
 - b. Treatment media
 - c. Internal distribution and collection piping
 - d. Pressure relief valve
 - e. Air/vacuum valve
 - f. Operating platform and/or ladder (optional)
8. Sample Panel (optional)
- a. Manifolds
 - i. Influent manifold (influent main sample and raw water samples from each treatment vessel after pH adjustment)
 - ii. Effluent manifold (effluent main sample after pH adjustment, treated water samples from each treatment vessel and wastewater manifold sample after pH adjustment and chemical injection)
 - iii. pH indicator (influent sample manifold and effluent sample manifold)
 - iv. Sample collection spigots with drain
 - b. Wet chemistry laboratory bench with equipment, glassware, reagents, etc.
9. Acid Storage and Feed Subsystem
- a. Emergency shower and eyewash, signage
 - b. Acid storage tank (outside treatment building)
 - i. Fill, discharge, drain, vent, and overflow piping
 - ii. Liquid level sensor (optional)
 - iii. Desiccant air dryer in vent (optional)
 - iv. Weather protection
 - v. Containment basin
 - c. Acid day tank (inside treatment building)
 - i. Fill pipe float valve
 - ii. Drain valve
 - iii. Containment basin
 - d. Acid pumps
 - i. Treatment unit pH adjustment
 - ii. Neutralization pH adjustment
 - iii. Wastewater pH adjustment (optional)
 - e. Acid piping (interconnecting piping)
 - i. Between storage tank and day tank
 - ii. Between feed pumps and raw water injection point
 - iii. Between feed pumps and regeneration feed and wastewater mains injection points (optional)

- iv. Backflow prevention
- 10. Caustic Storage and Feed Subsystem
 - a. Emergency shower and eye wash, signage
 - b. Caustic storage tank (outside treatment building)
 - i. Fill, discharge, drain, vent, and overflow piping
 - ii. Liquid level sensor (optional)
 - iii. Immersion heater with temperature control
 - iv. Weather protection
 - v. Containment basin (optional)
 - c. Caustic day tank (inside treatment building)
 - i. Fill line float valve
 - ii. Drain valve
 - iii. Containment basin (optional)
 - d. Caustic piping (interconnecting piping)
 - i. Between storage tank and day tank
 - ii. Between feed pump and, regeneration feed main injection point (optional)
 - iii. Between feed pump and treated effluent main injection point (optional)
 - iv. Backflow prevention
- 11. Backwash Water Disposal System (optional)
 - a. Surge tank (optional)
 - b. Lined evaporation pond (optional)
 - c. Unlined evaporation pond (optional)
 - d. Sewer (optional)
 - e. Drainage ditch (optional)
 - f. Other discharge method (optional)
- 12. Toxic Regeneration Wastewater Disposal System
 - a. Surge tank (optional)
 - b. Lined evaporation pond (optional)
 - c. Wastewater reclamation system (optional)
 - d. Other discharge method (optional)

Appendix B

Treatment System Design Example

This design example is applicable to a specific manually operated fluoride removal AA treatment system with two parallel vessels.

Given:

q (flowrate) = 600 gpm

N (number of treatment vessels) = 2

Raw water fluoride concentration = 5.0 mg/L

Treated water fluoride concentration = 1.0 mg/L (max)

AA fluoride removal capacity = 4,580 g/m³ (2,000 grains/ft³)

(Note: Indicated capacity applies only to system with a raw water fluoride concentration of 5.0 mg/L and a process water pH value of 5.5)

M_d (media packing density) = 48 lb/ft³

EBCT = 7.5 min (1 ft³/gpm)

Pipe material—Type I Schedule 80 PVC,

v (pipe velocity) = 5 ft/second (max.)

p (system pressure): 50 psig (max.)

T (ambient temperature): 95°F (max.)

T_w (water temperature): 85°F (max.)

1. Vessel and Treatment Bed Design (reference: Figure 3-4)

Solve for: h (treatment bed depth)

d (treatment bed diameter)

A (treatment bed horizontal surface area)

V (treatment bed volume)

M_w (total weight of treatment media)

D (vessel outside diameter)

H (vessel overall height)

q/N = 600 gpm/2 treatment beds = 300 gpm/bed

Then, using 1 ft³ of media per gpm of flowrate, we require 300 ft³ of A media per treatment bed (equivalent to an EBCT of 7.5 min), or

$$V = 300 \text{ ft}^3 = Ah = \pi d^2 h / 4$$

Then, when h = 5 ft,

$$A = 60 \text{ ft}^2 = \pi d^2 / 4$$

Then, d = 8.74 ft = 8 ft 8.8 in

Then, D = d + 1" = 8 ft 9.8 in, therefore use D = 9 ft 0 in (note: D must employ the next even multiple of 6 in)

Then, d = D - 1 in = 8 ft 11 in

Then, A = $\pi d^2 / 4 = \pi (8.92)^2 / 4 = 62.5 \text{ ft}^2$

Then, V = $\pi d^2 h / 4 = \pi (8.92)^2 (5) / 4 = 312 \text{ ft}^3$

Then, M_w = 2 vessels × 312 ft³ × 48 lb/ft³ = 29,952 lb

Because the media quantity is almost 30,000 lb, it is prudent to procure media in supersacks.

Then the vessel height (H) (Figure 3-4) is:

$$H = h + h/2 + 6 \text{ in} + (2)D/4 + 1 \text{ in} =$$
$$60 \text{ in} + 30 \text{ in} + 6 \text{ in} + 2 (108 \text{ in}/4) + 1 \text{ in} = 151 \text{ in} =$$
$$12 \text{ ft } 7 \text{ in}$$

2. Pipe Sizing

Solve for:

- a. Sizes of raw and treated water pipe mains
- b. Sizes of treatment unit branch piping

a. Mains:

$$Q = 600 \text{ gpm (max.)}$$

Try 6 in, $v = 6.5 \text{ in/sec} > 5 \text{ in/sec}$, therefore NG

Try 8 in, $v = 3.6 \text{ in/sec} < 5 \text{ in/sec}$, therefore OK

Use 8 in Schedule 80 PVC

b. Branches:

$$Q_B = q/w = 300 \text{ gpm}$$

Try 4 in, $v = 7.7 \text{ in/sec} > 5 \text{ in/sec}$, therefore NG

Try 6 in, $v = 3.4 \text{ in/sec} < 5 \text{ in/sec}$, therefore OK

Use 6 in Schedule 80 PVC

Backwash rate is not to exceed rate required for 50% treatment bed expansion.

Then, backwash rate = $A \times 7 \text{ gpm/ft}^2 = 62.5 \text{ ft}^2 \times 7 \text{ gpm/ft}^2 = 437.5 \text{ gpm} < 600 \text{ gpm}$, therefore OK.
(Note: The backwash rate is sensitive to water temperature.)

3. Acid Subsystem Design

a. Storage Tank Size

Storage tank size is based upon logistical requirements, which are a function of treatment plant acid consumption rate and bulk tank truck deliveries of acid. The tank truck can deliver up to 48,000 lb of 66°B' H₂SO₄. The density of this liquid is 15.5 lb/gal. Therefore, a delivery contains 3,100 gal.

In this example the peak treatment flow is 600 gpm, and it is assumed that the acid consumption as determined by titration is 0.05 gal/ 1,000 gal of treated water. Then the acid consumption is 1.8 gal/hr and a tank truckload would supply a minimum of 1,720 hr of treatment operation. Acid consumption for raw water pH reduction, which is a function of total alkalinity and free CO₂, is discussed in Appendix D.

A 5,000-gal acid storage tank provides capacity for more than 1½ bulk tank truckloads of 66°B' H₂SO₄. Therefore, when half a truckload has been consumed (providing capacity for the next truckload delivery), there is a minimum of a 860-hr acid supply available in storage before the acid supply is exhausted.

b. Day Tank Size

The storage tank supplies a polypropylene day tank located inside of the treatment building. A 100-gal day tank will satisfy more than 200% of the maximum treatment process pH adjustment acid requirements (i.e., 43.2 gal/day) for a maximum daily treatment flow of 864,000 gal.

c. Acid Pump Size

The acid feedrate required for the treatment process pH adjustment function is: $600 \text{ gpm} \times 60 \text{ min/hr} \times 0.05 \text{ gal acid/1,000 gal water} = 1.8 \text{ gph}$, which can be satisfied by a positive displacement diaphragm pump that has a maximum flowrate of 2.5 gph @ 50 psig with a 1,000:1 turndown capability (materials of construction to be recommended for 66°B' H₂SO₄ service).

For neutralization of the treatment bed after completion of regeneration and the regeneration wastewater flowing from the treatment vessel to the regeneration wastewater surge tank, two additional acid feed pumps are required. The rule of thumb relating to the volume of acid required to be applied to accomplish both functions is 1 gal/ft³ of AA, or 312 gal/regeneration. The acid feed for these two functions will take place over a period of 4 to 6 hr. The first pump feeds acid into the regeneration feedwater main to adjust the pH initially to 2.5, then to 4.0, and finally at completion of the neutralization to 5.5. The second pump feeds acid into the wastewater main at a rate required to adjust the pH of the entire wastewater batch to a range of 6.0 to 6.5. This latter acid feed requirement can take place at a constant rate that will provide the necessary wastewater pH for the volume of the entire wastewater batch (thoroughly mixed in the wastewater surge tank) at the conclusion of the regeneration process. The two acid feed pumps required for the two functions can be identical air-operated diaphragm pumps with maximum flowrate of 2 gpm at 50 psig with a 100:1 turndown capacity (materials of construction to be recommended for 66°B' H₂SO₄ service).

A 5-hp air compressor with a 60-gal receiver capable of supplying 14.7 cfm at 175 psig compressed air. The air compressor will supply compressed air for both air-operated diaphragm acid feed pumps, the air-operated diaphragm caustic soda feed pump, and (for automatic operation) the pneumatic-operated process control butterfly valves. If there is a wastewater sludge dewatering system, the air compressor will be available to operate the air-operated diaphragm pump (for sludge transfer) and the plate and frame filter press.

4. Caustic Subsystem Design

a. Storage Tank Size

Storage tank size is based upon logistical requirements, which are a function of treatment plant caustic consumption rate and bulk tank truck deliveries of caustic. A tank truck can deliver up to 48,000 lb of 50% NaOH. The density of this liquid is 12.9 lb/gal. Therefore, a delivery contains 3,700 gal.

In this example the peak treatment flow is 600 gpm, and it is assumed that the caustic consumption as determined by titration is 0.135 gal/ 1,000 gal treated water (Rubel F Manual uses 0.02). Then the caustic consumption is 4.86 gal/hr. Then, a tank truckload would supply a minimum of 760 hr of treatment operation.

A 5,000-gal caustic storage tank provides capacity for more than 1¼ bulk tank truckloads of 50% NaOH. Therefore, when 75% of a truckload has been consumed (providing capacity for the next

truckload delivery), 925 gal remains, which provides a 190-hr (8-day) caustic supply available in storage before the caustic supply is exhausted. Note: When the supply remaining in the storage tank provides capacity for a bulk tank truck delivery, spent media regeneration (if applicable) will be deferred until after caustic delivery.

b. Day Tank Size

The storage tank supplies a polypropylene day tank located inside of the treatment building. A 500-gal day tank will satisfy more than 200% of the maximum treatment process pH adjustment caustic requirements (117 gal/day) for maximum treatment flow of 864,000 gal for one day as well as the requirement (122 gal, see caustic pump size below) for one two-step regeneration of spent media.

c. Caustic Pump Size

The caustic feedrate required for the treatment process pH adjustment function is: $600 \text{ gpm} \times 60 \text{ min/hr} \times 0.135 \text{ gal caustic/1,000 gal water} = 4.86 \text{ gph}$.

The caustic feedrate required for the treatment process pH adjustment function (4.86 gph) is satisfied by a positive displacement diaphragm pump that has a maximum flowrate of 5 gph @ 50 psig with a 1,000:1 turndown capability (materials of construction to be recommended for 50% NaOH service).

For frequency of regeneration, the following is calculated:

Given:

Raw water fluoride concentration = 5.0 mg/L

Treated water fluoride concentration = 1.0 mg/L

AA media capacity = 2,000 grains/ft³

Bed volume = 312 ft³

Density of 50% NaOH = 12.9 lb/gal

Find: Regeneration frequency

Amount of fluoride removed = $5.0 - 1.0 = 4.0 \text{ mg/L} = 4.0 \times 0.058 = 0.23 \text{ grains/gal}$

Amount of water treated/treatment run/per vessel = $(2,000 \text{ grains/ft}^3 \times 312 \text{ ft}^3) / (0.23 \text{ grains/gal}) = 2,700,000 \text{ gal}$

Therefore, during maximum treatment flow continuous operation, minimum regeneration frequency would be six days per bed. Using the two bed system in this example, the maximum regeneration frequency could be as often as once every three days.

For regeneration of the AA treatment bed two regeneration steps are required utilizing 15 gal of 1% NaOH/ft³ of media per step. The following calculations provide the volume and flowrate of 50% NaOH required per regeneration.

Given:

d_1 = density of 1% NaOH = 8.4 lb/gal

d_2 = density of 50% NaOH = 12.9 lb/gal

v_1 = volume of 1% NaOH/regeneration step-ft³ = 15 gal/step-ft³

n = number of steps = 2 (upflow and downflow)
V = 312 ft³

Find:

w₁ = weight of 1% NaOH/step

v₂ = volume 50% NaOH required/step

Then, w₁ = v₁(V)(d₁) = 15 gal/step-ft³ × 312 ft³ × 8.4 lb/gal = 39,312 lb/step

Then, weight of 50% NaOH/step = 39,312 lb/50 = 786 lb/step

Then, v₂ = 786 lb/d₂ = 786 lb/(12.9 lb/gal) = 61 gal

Then: If, step duration is 50 min,

50% NaOH flowrate = v₂/50 min = 61 gal/50 min = 1.2 gpm

Then, total 50% NaOH required per regeneration = v₂ × n = 61 gal/step × 2 steps = 122 gal.

The caustic feed pump required for this function will be a 2 gpm metering pump with materials of construction suitable for 50% NaOH service. Each regeneration step (upflow and then downflow) requires 61 gal of 50% NaOH to be fed into the mixing tee where it is diluted to 1% NaOH. Each regeneration step is designed to last for 50 min.

5. Regeneration Wastewater Surge Tank Design

Given:

Maximum volume of regeneration wastewater per cubic foot media = 400 gal/ft³

Number of cubic feet of media per regeneration = 312 ft³

Tank construction – epoxy interior lined carbon steel

Find:

Volume of wastewater per regeneration = 400 gal/ft³ × 312 ft³ = 124,800 gal = 16,700 ft³

Dimensions of surge tank (use height = 20 ft)

Then, (diameter)² = 4 × 16,700 ft³/π × 20 ft = 1,063 ft²

Then, diameter = 33 ft

Suggested Containment Basin Dimensions: length 72 ft, width 64 ft, height 4 ft; volume = 18,400 ft³ = 137,600 gal > 124,800 gal.

6. Lined Regeneration Wastewater Disposal Evaporation Pond Design

a. It is assumed that the average plant utilization rate is 40% and that the annual average net evaporation rate is 6 ft 0 in.

b. Find: Evaporation pond size

Total annual volume of water treated = $40\% \times 600 \text{ gpm} \times 1440 \text{ min/day} \times 365 \text{ day/yr} = 126 \times 10^6 \text{ gal/yr}$

Amount of water treated/treatment run/vessel = $2.7 \times 10^6 \text{ gal}$ (see Section 4.c in Appendix B)

Then, number of regeneration cycles per year = 24.

Amount of wastewater per cubic foot of treatment media = 300 gal/ft^3 , then each regeneration cycle yields $300 \text{ gal/ft}^3 \times 312 \text{ ft}^3 \times 2 = 187,200 \text{ gal}$ of wastewater.

Then, total amount of wastewater produced per year = $187,200 \text{ gal} \times 24 = 4.5 \times 10^6 \text{ gal/yr} = 601,000 \text{ ft}^3/\text{yr}$

Using an average annual evaporation of 6 ft 0 in and deducting 1 ft 0 in for deviation from average, 5 ft 0 in is the net minimum evaporation rate per year.

Therefore, the required pond area can be calculated by dividing the total annual wastewater produced by the net minimum evaporation rate.

Pond area = $601,000 \text{ ft}^3 / 5 \text{ ft} = 120,200 \text{ ft}^2$ with 8 ft minimum pond depth.

Appendix C

Discussion of Acid Consumption Requirements for pH Adjustment of Raw Water

The practical method described in the text that is used to determine the acid feed requirement for lowering the raw water pH to 5.5 is acid titration. However, this can also be accomplished theoretically when a raw water analysis is available and raw water samples are not. This method requires pH, total alkalinity, and/or free carbon dioxide from the raw water analysis in addition to the graph illustrated in Figure C-1. If only two of the three raw water analysis items are available, the third is determined by the graph. The pH curves illustrated in Figure C-1 were developed from theoretical chemical formulae, which integrate the relationship between pH, alkalinity and free carbon dioxide. Trial and error usage of these curves can lead the designer to the acid feed requirement for the desired pH adjustment. The designer should be aware of the fact that the reduction in alkalinity coincides with the corresponding increase in free carbon dioxide. The following examples best illustrate this method:

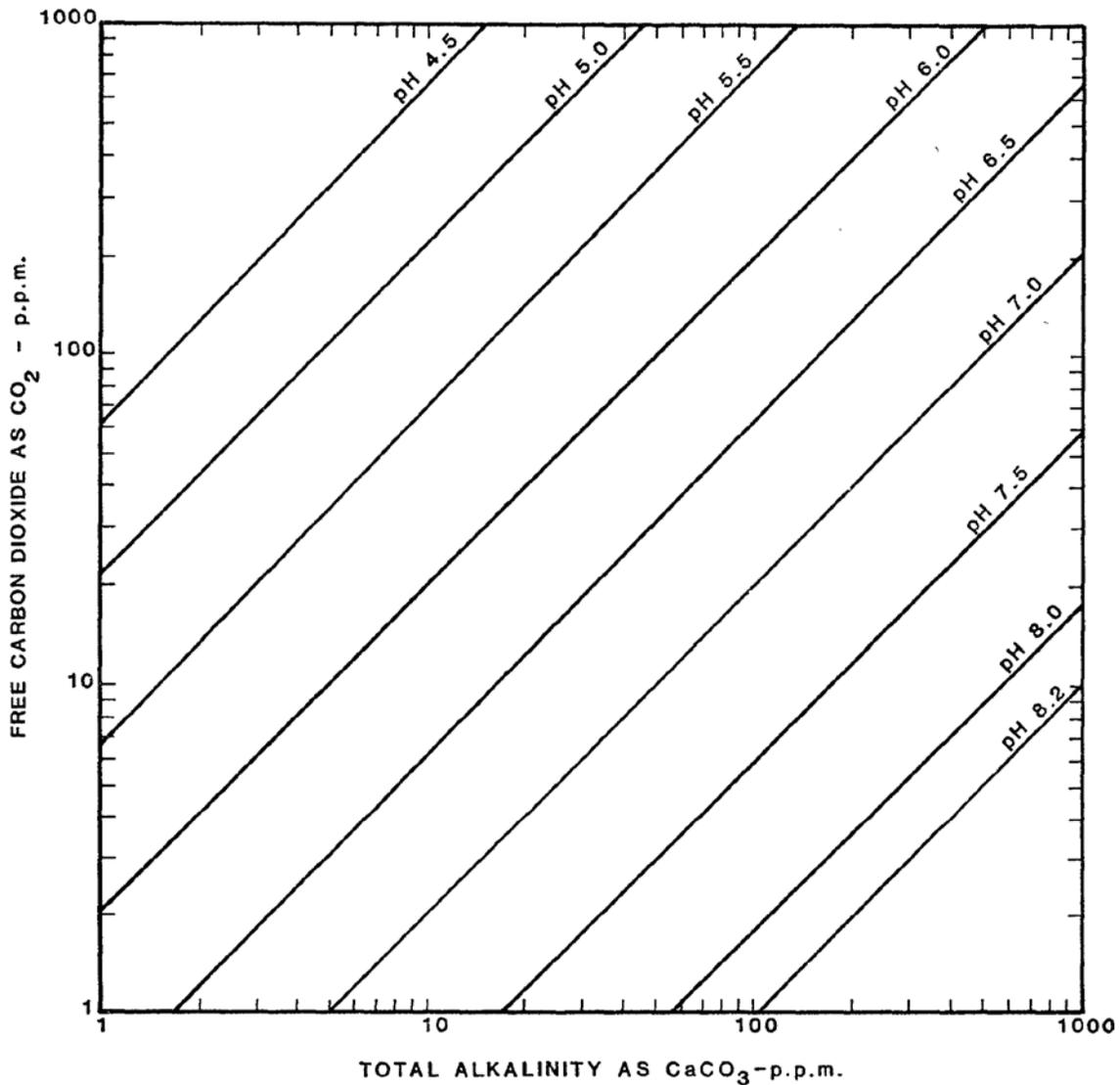


FIGURE C-1 GRAPH OF pH AS A FUNCTION OF TOTAL ALKALINITY AND FREE CARBON DIOXIDE

Example 1:

Given: Raw Water pH = 8.0
Raw Water M = 220 ppm (as CaCO₃)
Raw Water CO₂ = 4 ppm

Find: a) M and free CO₂ for pH adjusted to 5.5
b) 66 degree Sulfuric acid required feed rate to adjust pH to 5.5

a) Try reducing M by 200 ppm (as CaCO₃) to 20 ppm (as CaCO₃)

Then, increase in free CO₂ = 200 × 0.88 = 176 ppm

Then, total free CO₂ = 176 + 4 = 180 ppm

Then using the graph we find the adjusted pH to be 5.4 when:

1) M = 20 ppm (as CaCO₃)

2) Free CO₂ = 180 ppm

Therefore, too much alkalinity was removed, try reducing M by 196 ppm (as CaCO₃) to 24 ppm (as CaCO₃).

Then, increase in free CO₂ = 196 × 0.88 = 172.5 ppm

Then, total free CO₂ = 172.5 + 4 = 176.5 ppm

Then using the graph we find the adjusted pH to be 5.5 when:

1) M = 24 ppm (as CaCO₃)

2) Free CO₂ = 176.5 ppm

b) For each 100 ppm (as CaCO₃) reduction of total alkalinity, 105 ppm 66 degree sulfuric acid must be added. Therefore, reduce M by 196 ppm (as CaCO₃) by feeding 1.96 × 105 ppm = 205.8 ppm 66 degree sulfuric acid to adjust raw water pH to 5.5. If we desire to find what acid feed rate would be required per 1,000 gallons of treated water, we find that:

Feed rate = (205.8 × 10⁻⁶ ppm) × (1,000 gal × 8.34 lb/gal)/15.5 lb/gal = 0.11 gal H₂SO₄/1,000 gal water

Example 2:

Given: Raw Water M = 100 ppm (as CaCO₃)
Free CO₂ = 6 ppm

Find: a) Raw Water pH
b) M and free CO₂ for pH adjusted to 5.5
c) 66 degree Sulfuric acid required feed rate to adjust pH to 5.5

a) From graph we find raw water pH to be 7.5

b) Try reducing M by 80 ppm (as CaCO₃) to 20 ppm (as CaCO₃)

Then, increase in free CO₂ = 80 × 0.88 = 70.4 ppm

Then, total free CO₂ = 70.4 + 6 = 76.4 ppm

Then using the graph we find the adjusted pH to be 5.75 when:

1) M = 20 ppm (as CaCO₃)

2) Free CO₂ = 76.4 ppm

Therefore, too little alkalinity was removed, try reducing M by 87 ppm (as CaCO₃) to 13 ppm (as CaCO₃).

Then, using the graph we find the adjusted pH to be 5.55 when:

1) $M = 13 \text{ ppm (as CaCO}_3\text{)}$

2) $\text{Free CO}_2 = 82.5 \text{ ppm}$

Therefore, too little alkalinity was removed, try reducing M by 88 ppm (as CaCO_3) to 12 ppm (as CaCO_3).

Then, increase in free $\text{CO}_2 = 88 \times 0.88 = 77.5 \text{ ppm}$

Then, total free $\text{CO}_2 = 77.5 + 6 = 83.5 \text{ ppm}$

Then using the graph we find the adjusted pH to be 5.5 when:

1) $M = 12 \text{ ppm (as CaCO}_3\text{)}$

2) $\text{Free CO}_2 = 83.5 \text{ ppm}$

c) Therefore, reduce M by 88 ppm (as CaCO_3) by feeding $0.88 \times 105 = 92.4 \text{ ppm}$ 66 degree sulfuric acid to adjust raw water pH to 5.5.

Acid feed rate = $(92.4 \times 10^{-6} \text{ ppm}) \times (1,000 \text{ gal} \times 8.34 \text{ lb/gal}) / (15.5 \text{ lb/gal}) = 0.05 \text{ gal H}_2\text{SO}_4 / 1,000 \text{ gal water}$

Appendix D

Activated Alumina Plant Search and Visits

To facilitate the revision of the 1984 fluoride design manual and better understand the evolution of AA system design and operations, a list of active AA plants in the U.S. was identified and their design and operation information was collected. The search for the plants was conducted via a brief internet and literature search, followed by email and telephone communications with individuals such as state drinking water officials, technology vendors, and AA media manufacturers and suppliers. The time period covered for the search spanned from early 1960s when some of the earliest AA plants were first installed through 2013 when a 900-gpm newly designed and installed AA plant awaits system startup. The search focused on states such as Arizona, California, Idaho, New Mexico, Oklahoma, and Texas where significantly elevated levels of natural fluoride in drinking water supplies have been reported (CDC, 1992).

System information collected included, but not limited to, treatment type, technology/media vendors, system size, system footprint, system installation time, source water quality (i.e., fluoride level and pH at a minimum), process/design parameters, system operation and maintenance (O&M), performance/compliance monitoring, media regeneration, residual handling, and costs. The pieces of information were collected mostly through emails and phone calls, with some obtained via site visits (to three plants). Table D-1 summarizes the plants identified and design and operation information collected. Obviously, the plants shown in Table 3-1 does not represent an exhaustive list of AA plants currently operating in the U.S. Rather, they represent only those having relevant information available during the information collection period of this manual revision project. The plants are identified as Plants A through F.

While a number of variations exist in system design and operations (see Table C-1), the basic parameters remain essentially unchanged among the plants. For example, depending on the system flowrate, a plant comprises a minimum of two parallel vessels or multiple parallel lead-lag modules to accommodate the maximum daily demand. Each vessel is sized to contain a volume of AA that provides a minimum of 5 min EBCT. The depths of AA beds range between 3 to 6 ft and the straight side of a vessel will allow at least 50% AA bed expansion plus 6 in during media backwash. The materials of construction is suitable for exposure to acid and caustic used for pH adjustments during service and media regeneration. The media regeneration generally includes a backwash, a 1% caustic wash, and a sulfuric acid neutralization step. The 1984 design manual contains information consistent with all of these design and operating bases and therefore is considered still valid for use as guidelines for AA fluoride removal plant design and operations.

Table D-1. Activated Alumina Plant Design and Operational Parameters

	Parameter	Unit	Plant A	Plant B	Plant C	Plant D	Plant E	Plant F
General	Location		29 Palms, CA	Lordsburg, NM	Desert Center, CA	8 miles West of Blythe, CA	Blythe, CA	Ajo, AZ
	System Designed by		Fred Rubel Engineering	Severn Trent (SORB 09™ Process)	NA	Pureflow	NA	Malcomb Pirnie (Arcadia)
	System Constructed by		Pro Contracting/District	Severn Trent	NA	Pureflow	Third Tank by USFilter	A Construction Firm in Phoenix
	Time System On-line		Mar 2003	2009	1968 with one vessel replaced in 1995 and the other in 2001 or 2002	2013 (Still to be Started up)	NA	Apr 2011
Adsorption Vessels/Media	Number of Vessels		6	2	2	2	3	2
	Vessel Configuration		3 Parallel Modules	Parallel	Parallel	Series, but system runs with one tank at a time	Parallel	Parallel
	Vessel Diameter	Ft	11	12	14	11	12	8
	Vessel Height	Ft	12	NA	16	12	12	NA
	Vessel Straight Height	Ft	8	6	16	10	NA	10
	Vessel Construction		Epoxy-coated carbon steel	Carbon steel with NSF internal painting	Original - carbon steel with epoxy coating, replacement - one carbon steel with epoxy coating and one stainless steel	Carbon steel lined with epoxy	Steel	Carbon Steel with Epoxy Coating
	Vessel Pressure Rating	Psi	900	NA	Atmospheric (by gravity)	75	NA	120
	Media Type		Alcoa CPN	Alcan AA400G	Alcan AA400G	NA	Alcan AA400G	Alcan AA400G 14X28
	Media Volume	ft ³ /vessel	475	420	770	475	530	300
	Media Weight	lb/vessel	NA	20,160	36,960	22,800	25,500	NA
Media Bed Depth	Ft	5	3.7	5	5	4.7	6	
Free Board Depth	Ft	4.5	NA	NA	NA	NA	3.5	
Service	System Design Daily Flowrate	MGD	3	1.3	NA	1.3	NA	0.45
	System Design/Max. Pumping Rate	Gpm	2,100	900	NA	900	NA	300
	System Operating Flowrate	Gpm	1,650	720	500	900, but will run only at 500 gpm	2,100	300
	System Bypass Flowrate	Gpm	550	19%	NA	NA	NA	30
	Vessel Hydraulic Loading Rate	gpm/ft ²	5.8	3.2	3.2	5.3	6.2	6
Vessel EBCT	Min	6.5	8.7	11.5	7.1	5.7	NA	
pH Adjustment	Raw Water pH	S.U.	8	8.5	8.3	7.4	8.2	7.4-7.8
	Target Treatment pH	S.U.	5.0	6	5.6	5.5	5.5	8.3
	Effluent pH	S.U.	7.5-8.4	7.8	7.3-7.5	7.5	6.0-8.5	NA
	Acid Used		Sulfuric	Sulfuric	Sulfuric	Sulfuric	Sulfuric	H2SO4
Regeneration	Regeneration Frequency		1 vessel/day	~10 day (~3.2 MG throughput)	When F level is over 2 mg/L	TBD	Based on service throughput	Once per week per vessel
	Chemical Used		1% NaOH	1% NaOH	1% NaOH	1% NaOH	1% NaOH	1% NaOH
	Flow Pattern		Upflow/Downflow	Downflow	Downflow	Downflow	Upflow/Downflow	Downflow
	Acid Neutralization		Yes	Yes	Yes	Yes	Yes	Yes
	Disposition of Waste		Evaporation Pond	F ppt post treatment in place but not used	Evaporation Pond	Evaporation Pond	To wastewater Treatment Plant	Disposed to Sewer

NA – information not available

Appendix E

English to Metric Conversion Table

English	Multiply by	Metric
inch	0.0254	meter (m)
inch ²	0.000645	m ²
inch ³	0.000016	m ³
feet (ft)	0.3048	m
ft ²	0.0929	m ²
ft ³	0.0283	m ³
gallon (gal)	0.2642	liter (L)
gal	0.0038	m ³
gal	0.0038	kiloliter (kL)
grains (gr)	0.0649	gram (g)
gr/ft ³	2.2919	g/m ³
pounds (lb)	0.4545	kilogram (kg)
lb/inches ² (psi)	0.00689	megapascals (MP)
lb/ft ² (psf)	4.8922	kg/m ²
c/1,000 (gal)	0.2642	c/1,000 L